RADAR ANALYSIS OF TORNADOES

By

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Bachelor of Science

Tulane University

New Orleans, Louisiana

1950

Submitted to the Faculty of the Graduate School of
the Oklahoma Agricultural and Mechanical College
in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

1952

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PREFACE

Tornado tracking has been the subject of intensive research for the past few years at the Oklahoma Institute of Technology. Until now, however, no studies have been conducted using radar. The present investigation considers the potentialities of this new instrument in detail.

A number of typical as well as somewhat unusual tornadic situations have been analyzed. They have been reviewed in light of the meteorological and electrical methods available for use in this field, with a view of giving this project a broad perspective. A method for the integration of radar into the existing system is then proposed so as to improve the present technique of locating and tracking such storms. While it is conceded that radar alone is not capable of predicting the formation of tornadic cells, it is believed that when this device is used in conjunction with the sferic detector system, tracking will become rapid and reliable.

Several scope photographs have been made for weak, moderate and severe thunderstorm activity. These results are intended mostly as a verification of existing knowledge of radar meteorology and with the intent of aiding investigators who may continue this work.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to the library staff of the Oklahoma Agricultural and Mechanical College for making the more than fifty references available. The publications staff of the United States Air Force, Tinker Air Force Base, Oklahoma were very helpful by providing a copy of "Radar Storm Detection". Lt. Col. E. J. Fawbush and Major R. C. Miller of the United States Air Force have been most cooperative in furnishing information concerning the use of radar in meteorological applications. The hourly weather reports of frontal movements and thunderstorms, and the analyses of precipitation echoes made by Professor Hardy of the department of meteorology have been most valuable in preparing this study.

The foresight and guidance of the research director, Dr. Herbert L. Jones, has served as a constant source of inspiration to the writer. Mr. Jay Owens is one of the many unsung heroes who did so much to keep the equipment in operation. Professor Naeter was most helpful in advising the author on matters pertinent to this work. Much credit is due to the author's wife, Tensie, for her painstaking care in proofreading and typing the manuscript.

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CHAPTER I

PHYSICAL CHARACTERISTICS OF TORNADOES

The yearly occurrence of the "tornado season" is well known to the residents of Oklahoma and neighboring states. The violence of these, the worst of all storms, has been vividly described by numerous witnesses. Few people dare underestimate their destructibility. For many years, the exact time and place of tornado development was considered unpredictable. However, the research work carried on both in the field of meteorology and electrical engineering has given very promising signs of forecasting tornado formation.

Although tornadoes may occur at any time, they develop most frequently in the spring and early summer in Oklahoma. Cold dry air from the polar regions and northern Canada interact with warm humid marine tropical air to set off a violent chain of tornadoes. In the spring, these two air masses possess greater tornadic potential than at any other time. There are other instances of isolated cases of tornadoes forming during different seasons and under slightly different meteorological conditions, but the type described is by far the most common and the most destructive.

According to Humphreys,[1] the tornado is the world's most violent, yet, most well defined storm. The average diameter of

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1 W. J. Humphreys, Physics of the Air, p. 220.

the funnel at the surface of the earth is approximately 1000 feet, but it may vary from 40 feet to a mile. The horizontal and vertical wind velocities in the vortex of the whirl have never been measured, although observations of their effects have led to estimates.[2] Dry straws driven through wooden telegraph poles indicate that horizontal winds may be as high as 500 miles per hour. Reports of tornadoes lifting horse teams lead to estimates of vertical winds of 200 miles per hour. Tornadoes generally travel from southwest to northeast in the northern hemisphere at average velocities of 25 to 40 miles per hour, and for average path lengths of 20 to 40 miles. The humidity prior to the storm is generally excessive, as is the horizontal temperature and pressure gradient. The funnel extends from the base of a cumulonimbus cloud. The rapid helical motion of the funnel, due to intense vertical and horizontal wind components, causes expansion, cooling and condensation within the vortex. As a result, the spiraling pendant and its associated thunderhead have a very dark color.

Lloyd[3] has made a study of the synoptic conditions condusive to tornado formation. The most important requirement appears to be the presence of upper air cold fronts. Extremely severe tornadoes and thunderstorms occur when marine polar and

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2 William L. Donn, <u>Meteorology with Marine Applications</u>, p. 180.

3 J. R. Lloyd, "The Development and Trajectories of Tornadoes," <u>Weather Bureau Monthly Weather Review</u>, 70 (March, 1942), 65-75.

marine tropical air masses interact. The upper air cold fronts formed under these conditions are referred to as "conventional" or "true" upper air cold fronts.[4] A second type of upper air cold front, called "precipitation-induced" or "pre-cold frontal squall line", occurs as a consequence of marine tropical air mixing with a precipitation-cooled air mass. Tornadoes that develop in connection with the former type vary from as few as two to as many as fifteen in a single front. Moreover, they may last several hours. On the other hand, pre-cold frontal tornadoes generally occur singly, or at most in pairs, and usually last only a short time. The direction and speed of movement of the tornado may be determined approximately from the vector resolution of the direction and speed of the front, and the wind immediately ahead of the upper air cold front. Lloyd concludes that a steep lapse rate, or decrease of temperature with altitude, is a necessary condition for the formation of the group or family type. In addition, multiple tornadoes occur only in connection with marine polar cold fronts.

In the northern hemisphere, tornadoes frequently whirl in the counterclockwise direction. Some exceptions[5] have nevertheless been noted. Counterclockwise rotation is not attributed only to the rotation of the earth. It is due primarily

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4 Ibid., pp. 73-74.

5 J. L. Baldwin, "A Preliminary Report on Tornadoes in the United States during 1942," Weather Bureau Monthly Weather Review, 70 (February, 1943), p. 268.

to the fact that marine tropical air in the northern hemisphere is always moving from south or southwest to northeast. It thus moves to the right of northwesterly marine polar air, giving rise to vortices which, of necessity, must be counterclockwise. The violence of the tornado will depend largely upon: (1) The opposing wind velocities just ahead of, and just behind, the cold front; (2) The amount of moisture present in the marine tropical air; and (3) The slope of the upper air cold front. The tornado of May 30, 1942, at Lake Park, Iowa appears to support Lloyd's synoptic requirements.[6]

The initial whirl forms around a local convective column. Convective instability may be caused by gravity or the rapid lifting of tropical maritime air by a steep cold front.[7] The rotation is then strengthened by vapor condensation. It is necessary that the air currents drawn into the convective column either have different directions, or different velocities if in the same direction.[8] Furthermore, it is essential that moderately swift winds aloft are present to set up the initial rotation. When these conditions are fulfilled, the spiral begins to descend from the base of a huge cumulonimbus cloud. Since the rotational velocity is much greater than the relative

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6 Ibid., p. 268.

7 U. S. Weather Bureau, "On Synoptic Conditions for Tornadoes," Bulletin American Meteorological Society, XX (February, 1939), pp. 50-51.

8 Humphreys, op. cit., 222-223.

velocities of the initiating winds, Humphreys concludes that some other process is responsible for these intense whirls. He explains it by postulating that as masses of air, whose angular momenta are not zero, are drawn into the convective column the moment of inertia decreases. By the principle of conservation of momentum, this requires that the angular velocity must increase to keep the momentum unchanged. This rapidly revolving "wall of air" draws air from the surrounding atmosphere in from the bottom. The action of centrifugal force throws this newly drawn air to the periphery of the spiral. As a result, more air is drawn in due to the low pressure at the center. This action causes the funnel to burrow down through the atmosphere until it reaches the ground. This spiral then moves along with its cumulonimbus cloud. Whereas the tropical hurricane moves forward by adding to itself at the leading edge and discharging air at the trailing edge, the funnel of a tornado always moves with its parent cloud.[9] Thus while the hurricane is a whirling motion that moves through any space, the tornado travels as a separate entity, blown by the wind.

When tornadic conditions are present over water bodies, waterspouts develop with all the fury and violence of the conventional land tornado. However, a second type of waterspout has been known to develop due to the action of local convection.[10]

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9 Olus J. Stewart, "On the Motion of Rotating Storms," Bulletin American Meteorological Society, XX (September, 1939), pp. 389-390.

10 Donn, op. cit., 183.

This whirl is somewhat different from tornadoes in that it may rotate in either direction and rarely lasts longer than an hour. Furthermore, it is generally mild by comparison to the tornado. The dust whirl, frequently observed in desert areas, is believed due to local heating and convection in a manner very similar to convective-waterspouts.

The mechanism of thunderhead development has also been the subject of extensive research.[11] Cumulonimbus thunderclouds may form under the following conditions: (1) Local convective activity due to heat being taken from the surface of the earth; (2) Topographical effects such as steeply sloping mountains; and (3) Steeply sloping cold fronts. When a body of air containing considerable moisture is heated, it rises to an altitude at which the water vapor condenses, forming a cloud. Likewise a strong wind flowing up the side of a mountain may also raise such humid air to the dew point, at which condensation occurs. These two effects, stated above in (1) and (2), are responsible for most "air mass" thunderstorms.[12] The third method, in which warm humid air is subjected to rapid lifting due to an underrunning and steeply sloping cold front, is the basic mechanism by which cold front thunderheads are developed. Regardless of how it begins, the process continues to develop a strong convective cell within the center of the cloud. This cell grows in

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11 U. S. Air Force, Navy, National Advisory Committee for Aeronautics, and Weather Bureau, The Thunderstorm, Report of the Thunderstorm Project.

12 Donn, op. cit., 83-86.

a vertical direction increasing the cloud height. Until the 0°C isotherm is reached, the condensed water vapor remains in liquid form. However, above this level it becomes snow and ice. The cloud ultimately reaches a leveling off point where vertical development ceases. The cloud, as a whole, moves under the influence of the motivating winds. Shearing effect causes the top of the cloud to slide and flatten relative to the base, giving an anvil shape. The lower forward edge of the cloud base contains a roller or squall cloud,[13] which may be visualized as a long, relatively small diameter, cylinder. The turbulence within this portion of the cloud is particularly severe. The cloud also grows in horizontal as well as in vertical extent, until, at maturity, the two dimensions are comparable.[14] The horizontal and vertical dimensions of the updraft or convective column in the cloud vary from 20,000 to 60,000 ft. The average dimension is approximately 40,000 ft. Maximum updraft velocities of 84 ft. per second have been measured.[15] Some meteorologists contend[16] that the most violent thunderstorms have the greatest vertical development. Others[17] specify excessive vertical draft velocities as the criteria of violence approach-

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13 Ibid., p. 84.

14 U. S. A. F., Navy, N. A. C. A., Weather Bureau, op. cit., pp. 39-46.

15 Ibid., p. 40.

16 Donn, op. cit., p. 84.

17 Humphreys, op. cit., pp. 218-220.

ing tornadic conditions. It will be seen later that both these properties of thunderstorms will be useful in tornado analysis. Mammato cumulus clouds often precede the onset of tornadic conditions and are generally indicative of bad weather. As they would probably be obscured by darkness, this method alone may be unsatisfactory for precise tornado predictions.

The electrical activity associated with thunderstorms and tornadoes has also been the subject of extensive research. It has been found that a tremendous electric charge is built up in the convective center. Although the physical processes involved are quite different, the convective cell may be likened to the Van de Graff electrostatic generator,[18] producing a negative charge at the bottom and a positive charge at the top. Workman and Reynolds[19] have conducted thorough studies of the mechanism of charge build up in thunderstorms. The results of their work seem to indicate that the formation of hail within the thunderhead is a definite requirement for charge separation to take place. This implies that all thunderstorms exhibiting any electrical activity whatsoever contain some amount of hail, although it may vary in quantity from storm to storm. They propose the theory that water falling in the vicinity of the $0^{o}C$ isotherm collides with and shears off hail moving upward

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18 J. B. Hoag and S. A. Korff, Electron and Nuclear Physics, pp. 309-312.

19 E. J. Workman and S. E. Reynolds, "A Suggested Mechanism for the Generation of Thunderstorm Electricity," Physical Review, 74 (July, 1948), p. 709.

due to strong convective activity. Part of the water freezes to the surface of the hail, producing a negative charge on the ice. The water leaving the ice assumes a positive charge. Careful analysis of these results indicate that a negative charge center occurs very near the freezing level, and a small concentrated positive charge occurs just below it. Also, the heavier ice particles sink to the base of the cloud while many of the lighter, positively charged drops are carried to the top of the cloud. This conclusion appears to agree with the cloud charge distribution model originally developed by Simpson and modified to conform to Schonland's experimental work, and C. T. R. Wilson's theory.

As the thunderhead progresses through its life cycle from inception to maturity to dissipation, major electrical activity varies from intra-cloud to cloud-to-ground to intra-cloud, respectively. Intense electrical activity is known to be associated with most tornadoes, although, according to Humphreys, severe lightning occurs more commonly with the parent cumulonimbus than with the funnel itself. Witnesses of tornadoes claim that the lightning is most frequently pink or orange whereas in mild thunderstorms it is generally white or yellow.

A number of tornadoes have been observed which bear out the foregoing characteristics. At 3:45 p.m., April 27, 1942, a tornado struck Pryor, Oklahoma,[20] killing 52 persons and

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20 Baldwin, loc. cit.

injuring 181. The damage was estimated at $2,000,000.00. The least destructive tornadoes reported in the United States in 1942 occurred in August in the State of Kansas. Eight funnel clouds were observed in connection with three storms, seven of which did not reach the ground, and six of which formed from the same thunderhead. Furthermore, a study of the tornadoes occurring in Nebraska[21] over a 22 year period indicate that 95% of all tornadoes developed in connection with cold fronts. Another severe tornado which occurred near Dallas, Georgia,[22] April 7, 1938, at 7:30 p.m., wreaked untold havoc. A witness described it in detail. The storm exhibited all the foregoing typical properties. Eleven out of fourteen tornadoes occurring near St. Louis, Missouri,[23] in 1948 occurred with severe rain, hail, and intense electrical activity.

In contrast to the above situations which support the cold front theory of tornado development, a number of exceptions as to properties or source have been observed. A severe tornado struck south of Oklahoma City, Oklahoma,[24] at 8:41 p.m., June 12, 1942. 35 persons were killed and 29 were seriously

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21 M. Lemons, "Cold Fronts and Tornadic Inception," <u>U. S. Weather Bureau Monthly Weather Review</u>, 66 (July, 1938), p. 206.

22 Alfred C. Hawkins, "A Tornado in Georgia," <u>Bulletin American Meteorological Society</u>, XX (February, 1939), p. 52.

23 E. M. Brooks, "Some Characteristics of Tornadoes in 1948 Near St. Louis," <u>Bulletin American Meteorological Society</u>, XXIX (December, 1948), p. 520.

24 Baldwin, <u>loc. cit.</u>

injured. A total of 73 homes were completely destroyed and 31 others were damaged. Very little rain and no hail was present. However, there was a great deal of mud in the funnel cloud! An aviator piloted a sail plane through a thunderhead[25] near Wichita Falls, Texas, July 17, 1947. Although turbulence was severe, and a great deal of lightning was observed, very little ice and hail were present. The previously mentioned study of tornadoes in Nebraska[26] showed that 1% definitely occurred in connection with a warm front; 3% are believed to be due to a warm front, but evidence is not certain; and 1% show no apparent cause for formation at all. Three of the tornadoes occurring near St. Louis in 1948 showed no observable lightning or precipitation.[27]

Furthermore, Professor C. F. Brooks[28] pointed out that under certain conditions when the relative humidity beneath the cloud base is very high, funnel-shaped cloud structures have been observed on the ground; but with no destructive winds present. Professor Brooks further stated that tornadoes are frequently present without visible lightning or thunder. Common characteristics such as the funnel may be obscured by low hanging clouds. It therefore appears, that the only

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25 J. H. Ferguson, "Soaring Flight in a Thunderstorm Cloud," Bulletin American Meteorological Society, XXVIII (December, 1947), p. 452.

26 Lemons, loc. cit.

27 Brooks, loc. cit.

28 Ibid., p. 520.

important requirement in specifying a tornado is the destructive rotary winds.

The above exceptions to the typical case show that the conditions under which tornadoes form, and the physical properties they exhibit, are subject to at least a slight degree of variation. These results clearly indicate that if any tornado warning system is to be completely reliable, it must not depend only upon the determination of one tornadic characteristic. For example, an adequate warning system cannot depend only upon the electrical phenomena, or the pressure variation, or the hail or precipitation content. It is essential that the system must be an integration of all existing tornado properties, and must include a means for cross-checking each against the other. And most important of all, the system must be the result of the cooperative effort of the meteorologist and the electrical engineer.

CHAPTER II

THE FEASIBILITY OF PREDICTING AND DETECTING TORNADOES

A study of the foregoing characteristics of tornadoes has led to several attempts to predict their formation. Regardless of the number of methods proposed, they have been either of a meteorological or electrical nature.

One of the most successful meteorological systems devised is "The Empirical Method" of Fawbush, Miller, and Starrett.[1] The method is as follows:[2]

> "After a lengthy investigation of a large number of synoptic situations in the United States prior to 1949, it was found that tornado situations developed when, and only when, the synoptic situation was characterized by the following conditions:
>
> (1). A layer of moist air near the earth's surface must be surmounted by a deep layer of dry air.
>
> (2). The horizontal moisture distribution within the moist layer must exhibit a distinct maximum along a relatively narrow band (i.e., a moisture wedge or ridge).
>
> (3). The horizontal distribution of winds aloft must exhibit a maximum of speed along a relatively narrow band at some level between 10,000 and 20,000 feet, with the maximum speed exceeding 35 knots.
>
> (4). The vertical projection of the axis of wind maximum must intersect the axis of the moisture ridge.

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1 E. J. Fawbush, R. C. Miller, and L. G. Starrett, "An Empirical Method of Forecasting Tornado Development," Bulletin American Meteorological Society XXXII (January, 1951), pp. 1-9.

2 Ibid., pp. 4-5.

(5). The temperature distribution of the air column as a whole must be such as to indicate conditional instability.

(6). The moist layer must be subjected to appreciable lifting.

Some of the above rules have been individually expressed or implied in previous literature ...., but successful forecasting depends on consideration of the complete set.

It should be noted that the above conditions must be satisfied simultaneously at the time of the first appearance of tornadoes and similar storms. Synoptic situations preceding tornado development are often characterized by the presence of the above conditions but in separate areas. The forecasting problem is then usually limited to determining whether or not the air motion is, or will be, such as to bring the different favorable areas to coincidence. At other times, one or two of the conditions may not be satisfied initially, but become so within 12 to 24 hours. In all cases examined, at least four of the six conditions have been fulfilled 12 hours prior to the outbreak of the storm, the remaining ones becoming satisfied by the time of outbreak.

Owing to the sparsity of reporting upper wind stations, condition (3) above is usually the one that offers the greatest difficulty, with the possible exception of condition (6). In about 80% of the cases examined, the wind maximum was determined from wind observations. In the remaining 20% of the cases, the maximum was determined from the pressure-contour charts."

Evaluation of the above criteria become involved for untrained personnel. For this reason it will probably be necessary to retain the services of a competent meteorologist.

Records available in the United States Weather Bureau indicate that the year may be divided into three periods of tornado activity: (1) The spring and early summer, March through June. During this period two-thirds of all tornadoes occur; (2) The late summer and early autumn, July through September. One-fifth of all tornadoes occur at this time;

(3) The late autumn and early winter, October through February. At this time one-seventh of all tornadoes occur.

It appears also, that topography indirectly influences the location of most severe tornadic activity. While tornadoes have occurred in every state, the frequency of occurrence is much greater in the Great Plains than in any other region of North America.

The foregoing system of Fawbush, Miller, and Starrett has been definitely verified on a number of occasions. In 1948, these authors predicted one tornado that occurred. In 1949, 14 tornadoes substantiated their forecasts. In 1950, 17 tornadoes verified their predictions. This work appears to be a most important contribution in forecasting tornadoes.

A second meteorological method[3] of predicting tornadoes has been proposed by Morris Tepper. It is shown[4] that a shock wave may be set up by a rapidly moving front. The shock wave gives rise to a slight condensation of air masses subjected to this effect. This in turn, causes the pressure at the leading edge of the wave to exhibit a relatively sharp discontinuity with the remaining air particles. Tepper proposes that the north-south pressure jump is a pre-cold frontal pressure-jump, induced by accelerations of the front. Likewise, the east-west

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3 Morris Tepper, "On the Origin of Tornadoes," Bulletin American Meteorological Society XXXI (November, 1950), pp. 311-314.

4 Morris Tepper, "Proposed Mechanism of Squall Lines: The Pressure-Jump Line," Journal of Meteorology, VII (February, 1950) pp. 21-29.

pressure-jump is associated with accelerations along a warm front, due to temperature inversion. When these two unequal pressure-jumps intersect, vortex sheets or contact discontinuities are set up in their zone of interaction. This interaction zone is characterized by sharp wind shear, which, under suitable thermodynamic conditions, is favorable to the development of tornadoes.

An important hypothesis of Tepper's theory is that the pressure-jump is not related to the front which produces it. He corroborates this supposition with the reports[5] of several tornadoes reported near St. Louis in 1948. The tornadoes seemed to exhibit features uncommon to the most frequently encountered ones. These, for example, occurred without any visible electrical activity.

Frequent microbarometric surveys are required at several points of observation in order to detect the presence of such a pressure-jump. It appears that the necessity for accurately timed, precise pressure readings may limit the advantages of this method. Moreover, this system seems to be limited to weather stations equipped to make such readings. It follows, therefore, that the most significant feature of this method is to verify "The Empirical Method". Furthermore, this system is relatively new and will, in all probability, have to be investigated more completely before it may be regarded as a self-sufficient criteria for tornado development.

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5 Brooks, op. cit., p. 520.

The "Sferic Detection System" is an electrical method which has been the subject of considerable investigation.[6] It consists, essentially, of a radio receiver designed to pass all low frequencies below approximately 500 kc. This information is displayed on a cathode ray oscillograph. A clock and synchronized camera are integral parts of the equipment used for obtaining properly dated and timed photographs. A direction finder[7] has also been added so that the direction from which the sferic originated may be determined. This information may also be checked against the AN/GRD-1A, Static Direction Finder, developed by the United States Army Signal Corps.

Hess[8] found that while all thunderstorms contain low frequency sferics, tornadoes possess appreciable high frequency components as well. The exact value of these high frequency components is not known at this time. From the sweep frequency settings of the oscillograph, and from counts of the number of cycles present, these components have been estimated to be approximately 200 kc. Due to attenuation and other factors, it has not been possible to establish any relationship between the amplitude of the sferic and the range. Attempts to determine the range from sferic wave forms have been under investigation

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6 Philip N. Hess, Installation and Operation of Electronic Sferic Detection Equipment, Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1951.

7 Vernon D. Wade, Development and Operation of a Crossed Loop Sferic Direction Finder, Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1951.

8 Hess, op. cit., pp. 48-49.

at the University of Florida.[9] The results of this work have largely been unsuccessful.

Another major disadvantage of the sferic detection system, at its present stage of development, is its inability to distinguish incipient tornadoes from fully developed ones.[10] Incipient tornadoes are those which either remain in the thunderhead, or, which just start to form visible funnels and then break up. According to Hess,[11] the energy necessary for the formation of incipient tornadoes is only slightly less than for those that do actually occur. For this reason, a number of severe thunderstorms, particularly those occurring at the height of the tornado season, give the same indications as the most violent manifestations of nature. It is believed that if tornado warnings were issued only on the basis of received sferics, the community would frequently be alerted when only incipient conditions prevail. It is thought that such "false alarms" would lead to apprehension by citizens as to the effectiveness of such a system.

It is the view of the project director, Dr. H. L. Jones, that a more accurate study of these waveforms could be achieved

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9 W. J. Kessler and C. W. Goyder, Distance Determination to Thunderstorm Areas Through Waveform Analysis of Associated Atmospherics, Department of Engineering and Industrial Experiment Station, University of Florida, Gainsville, Florida, (1948).

10 Hess, *op. cit.*, pp. 50-51.

11 Ibid., pp. 50-51.

by incorporating a filter to eliminate the low frequency components. Future research may also suggest the use of a number of tuned circuits to select specific high frequency components which may be related exclusively to the incipient or mature tornado.

Hess also proposes the investigation of two other fundamental properties of the sferic wave, e.g., its waveform and duration. The work of Harder and Clayton[12] would support waveform studies. The "cold lightning stroke" is one of high current and relatively short duration. The pulse duration ranges from 100 to 1000 microseconds. It has an explosive effect, causing objects to blow apart upon being struck. The "hot lightning stroke" is one of much smaller amplitude and much longer pulse duration, ranging from 2,000 to 10,000 microseconds. It has an incendiary effect causing objects to burn. This type is believed to be the cause of many forest fires.[13] Until research can definitely establish information to the contrary, it is conceivable that either of these types might predominate in the incipient or the fully developed tornado.

Hess witnessed a tornado west of Stillwater, Oklahoma.[14]

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12 E. L. Harder and J. M. Clayton, "Lightning Phenomena," The Westinghouse Engineer, (July, 1951), pp. 106-111.

13 Ibid., p. 107.

14 Hess, loc. cit.

Intense lightning was observed close to the funnel. These strokes were decidedly orange and appreciably different from those at some distance from the funnel, but in the same thunderhead. This appears to be another exception to Humphreys' description of electrical activity in a typical tornado.[15] The observer claims that these strokes appeared to be of longer duration, although he was aware of the fact that this may have been an optical illusion. Illumination from sources of great brilliance tend to alter the persistency of vision, when falling upon the eye. Nevertheless, experiences such as these suggest the investigation of the third property of sferics, e.g., pulse duration. To date, no work appears to have been undertaken in this phase of the problem.

There is one additional qualitative phase of the study which Dr. Jones has considered. With the assistance of a graduate student, the director has demonstrated that those lightning strokes which are orange or pink apparently generate the high frequency sferics. During a recent storm, Dr. Jones observed the oscillograph while the student watched for this color of lightning. Each time the assistant observed such a stroke, the high frequency wave appeared on the screen.

Another electrical method has been investigated in an effort to detect the onset of tornadic conditions. It might be

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15 Humphreys, op. cit., p. 306.

called the "magnetometer method". It is known[16] that during fair weather electric lines of force issuing from a region believed beyond the earth's atmosphere, terminate on its surface. Accordingly, the earth bears a negative charge relative to the surrounding atmosphere. During severe thunderstorm[17] activity the lines of force change direction in the vicinity of the storm. The earth is then positive with respect to the air in the immediate vicinity of the storm. A magnetometer[18] has been developed which indicates both the sign and magnitude of this change. A permanent record is kept on an instrument similar to the recording type ammeter.

According to Grubbs,[19] very little correlation exists between changes in the magnetic field and prevailing weather conditions. He has noted that on some fair weather days no magnetic variation occurred, while on others frequent changes were observed. It is reasonable to conclude that these variations might be due to airplanes taking off and landing on a nearby runway. This possibility is supported by Johnson's findings.[20]

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16 K. B. McEachron and Others of the General Electric Company, Lightning and the Protection of Electric Systems, GEA-3173 (1939).

17 Ibid.

18 David L. Johnson, An Electronic Magnetometer, Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1950.

19 William C. Grubbs, Jr., Weather, Atmospheric and Tornadic Disturbances and Their Effects on Changes in the Earth's Magnetic Field, Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1951, p. 50.

20 Johnson, op. cit., p. 36.

Before the magnetometer was moved to its present position at the airport, the passing of automobiles on the campus near the engineering building completely disrupted the operation of the equipment.

Although Grubbs found[21] that some magnetic variation existed during thunderstorm activity, no definite relationship could be reported. Furthermore, magnetic variation in both fair and inclement weather may be more strongly influenced by phenomena such as magnetic storms and other sudden ionispheric disturbances which have relatively little bearing upon local weather conditions. If these results may be regarded as reliable, it is clear that this method is somewhat questionable for tornado forecasting.

Furthermore, in the instances which arise wherein little or no observable electrical activity exists with tornadoes, as described in Chapter I, it appears that neither the sferic detection method nor the magnetometer method would be of any great value.

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21 Grubbs, op. cit., pp. 50-51.

CHAPTER III

REQUIREMENTS OF A METEOROLOGICAL RADAR

During World War II many radar operators observed echoes from areas experiencing thunderstorms and heavy precipitation. Airplanes, ships, tall structures, or other physical objects were frequently not present in the region producing the radar echo. Even in instances where such objects were present, the precipitation echo could be distinguished by its form and motion. To many operators, particularly those engaged in night bombing by radar, the appearance of weather echoes was a disturbing influence. In some cases it prevented a mission from carrying out its assigned duty. Meteorologists recognized, however, that this new instrument could aid the forecaster in short range predictions and in verifying certain anticipated conditions. Towards the close of the war the various military and naval services undertook extensive study and investigation in the rapidly growing field of "Radar Meteorology". Data from all parts of the world were gathered, studied and cataloged for future reference. With the lifting of security restrictions that followed the end of hostilities, this material was made available to scientists, meteorologists, and engineers concerned with weather research. Published reports of wartime activities[1] indicate that practically all types of weather phenomena capable of appearing on oscilloscopes have been observed

1 R. H. Maynard, Commander, U. S. N., "Radar and Weather," Journal of Meteorology, II (December, 1945), p. 215.

and photographed, with the exception of tornadoes. It is the main purpose of this study to suggest possible methods by which radar can be integrated into existing systems for effecting positive identification of expected tornadic conditions.

In its simplest form, radar consists of a transmitter, receiver, synchronizer, and appropriate indicating device, as shown in Fig. 1. The frequency of the transmitter and receiver is usually between 3,000 and 10,000 megacycles. The transmitter radiates an extremely large amount of power for a very small period of time. The power usually is from 50 kilowatts to 1 megawatt, and the transmission time, or pulse time, is generally about 1 microsecond.

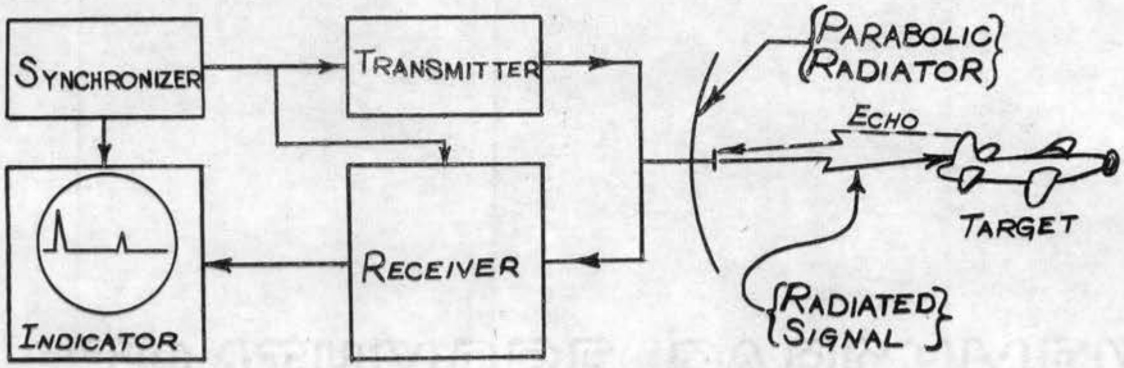

Fig. 1. Block diagram of a radar system.

About 1,000 of these pulses are transmitted each second. This is described by signifying that the pulse recurrence frequency, or p.r.f., is 1,000 cycles per second. During the time when no pulse is being transmitted, the receiver is operative. If there is an airplane, battleship, or some other target in line with the radar beam, some of the energy which strikes it will be reflected back to the radar set. The receiver will detect this small amount of reflected energy and will amplify it. By suitable means, this echo is displayed on a visual indicator called a cathode ray oscilloscope. In radar parlance the name is frequently shortened to radar-scope, or simply scope. The radiating system consists of a small antenna mounted at the focal point of a parabolic reflector. In this manner a highly directive beam is formed. Such an arrangement concentrates the energy so as to achieve a long range and at the same time permit the accurate determination of azimuth and elevation. The synchronizer is an electronic timer which turns the transmitter and receiver on and off at precise intervals. Furthermore, the synchronizer controlls the operation of the indicator so that returning echoes may be read directly in yards or miles. Just as the transmitter starts generating energy, the synchronizer activates electrical apparatus which starts a line on the scope. The line continues to move across the scope even after the transmitter is turned off. The line reaches its terminus just as the time has elapsed corresponding to the most distant target for the range selected. Then the line is retraced, beginning as the transmitter sends out a second pulse. This entire process is repeated at the pulse recurrence frequency of the set.

A number of cathode ray tube displays have been developed,[2] but only those important in meteorological applica-

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2 Federal Telephone and Radio Corporation, Reference Data for Radio Engineers, pp. 464-465.

tions will be considered. The simplest sweep is called the A-scope, Fig. 2. Amplitude in the vertical direction is plotted versus range in the horizontal direction.

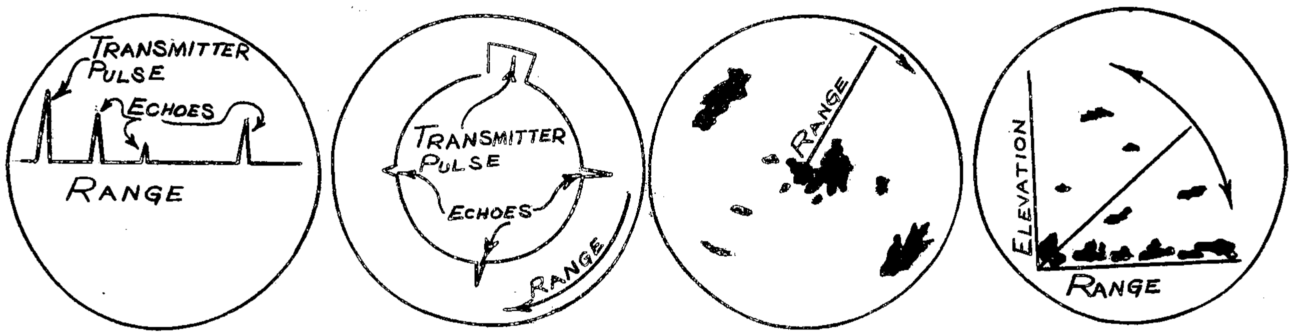

Fig. 2. Important cathode ray tube displays.

The first pulse is caused by energy flowing directly from the transmitter to the receiver. An auxiliary indicator must be provided to show the azimuth and elevation of the antenna. All targets appear as vertical spikes, called pips. The intensity increases as the antenna is brought in line with the target, and as the range to the target is decreased. The height of the transmitter pulse represents the saturation level, since no echo regardless of strength can exceed this amplitude. The range will usually vary from 20 to 100 miles, depending upon equipment settings. When a high degree of range accuracy is desired, an auxiliary A-scope, called an expanded A-scope[3] is provided. The expanded A-scope is exactly like the one shown above, except that its entire length of base line represents only 5 miles. Associated electronic equipment allows any five

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3 U. S. Air Force, Radar Storm Detection, A. F. Manual 105-30, p. 18.

mile interval within the range of the main A-scope to be chosen.

The J-scope increases the accuracy of reading the range by using a curved base line. The length of the line is approximately 3.14 times greater than the A-scope having the same diameter. The transmitter pulse appears at the top of the scope and its width is equal to the pulse width. As with the A-scope, the amplitude of the transmitter pulse just reaches the saturation level. The range is read clockwise from the top. The J-scope also requires auxiliary indicators to show the azimuth and elevation of the target. The principal feature of this display is its greater accuracy over the A-scope of equivalent dimensions.

The plan position indicator, PPI-scope, employs a radial sweep which rotates at the antenna speed. Range is read radially outward from the center and azimuth appears directly on the scope. For a fixed installation the antenna is usually adjusted so that when the radial trace is straight upward, the radar signal is directed toward true north. For a ship or aircraft, this line usually is parallel to the longitudinal axis. Any target can then be determined relative to the craft's heading. This display is referred to as "intensity modulated" since a target appears as a dot or smear of light on the scope. Only an approximation can be made of the amplitude of the echo. It is common practice to have the antenna revolve clockwise, although provisions are generally available for counterclockwise rotation and for adjusting the brilliance so that the revolving line just fades out with no incoming signal. The effect of the transmitter pulse can be observed by a bright spot of light at the center. An auxiliary indicator is necessary to give the elevation angle of the antenna. An A-scope is usually added when it is desired to measure echo signal strength. This display has found wide use both in military and meteorological applications.

The range height indicator, RHI, was first used on gun-laying radar. Later on it was used in ground controlled approach (GCA radar). Because this display gives an accurate indication of height, it has found wide use in radars adapted for meteorological applications. Height or elevation is plotted versus range. The elevation scale is usually made ten times as large as the range scale. Typical dimensions are 6 miles on the vertical scale and 60 miles on the horizontal scale. This scope also employs intensity modulation. Additional equipment is necessary to determine the azimuth of the antenna. The most important meteorological advantage of this scope presentation is its ability to provide vertical cross section patterns of precipitation and thunderclouds. It can be used for determining the height of convective cells within clouds. The RHI is the most accurate type of display for measuring the vertical growth rate of convective cells.

Table I. Radar Band Designation, Frequency and Wavelength.

Band Designation	Frequency in Mcs.	Wavelength in Cm.
P	225 - 390	133 - 77
L	390 - 1,550	77 - 19.4
S	1,550 - 5,200	19.4 - 5.77
X	5,200 - 11,000	5.77 - 2.73
K	11,000 - 33,000	2.73 - 0.91

Table I gives the band designations, frequencies and wavelengths in common use in radar applications.[4] The two most widely used frequency ranges are the X and S bands. In particular, the frequencies of 9,375 megacycles or 3.2 centimeters, and 3,300 megacycles or 9.1 centimeters, have been used extensively in radar work. As will be discussed later, the frequency chosen for a given radar will influence its range and power requirements.

An important consideration in determining whether a certain object will be detected by a radar set is its "target echoing area". This echoing area or radar cross section, as it is commonly called, may be defined[5] as "4 π times the ratio of the power per unit solid angle scattered backward toward the transmitter, to the power per unit area striking the target." For structures which are large in proportion to the wavelength, and which are relatively complex, the target echoing area varies rapidly with the angle of incidence. The radar cross section has been calculated for a number of important configurations.[6] These results are listed in Table II.

The resolving power, or the ability of a radar to distinguish two or more closely situated objects at long ranges, becomes important when the dimensions and numbers of targets have to be ascertained. A study of Figs. 3 and 4 shows that

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4 Federal Telephone and Radio Corporation, op. cit., p. 461.

5 Ibid., p. 462.

6 Ibid., pp. 462-463.

Table II. Radar Cross Sections of Important Configurations.

Type of Reflector	Cross Section
Tuned Dipole (Half-wave Radiator)	$0.22\lambda^2$
Small Sphere (Radius = a) $a/\lambda < 0.15$	$9\pi a^2(2\pi a/\lambda)^4$
Large Sphere (Radius = a) $a/\lambda > 1.0$	πa^2
Corner Reflector with One Edge = a (Maximum)	$4\pi a^4/3\lambda^2$
Flat Plate with Area = A (Normal Incidence)	$4\pi(A/\lambda)^2$
Cylinder with Radius = a, Length = L (Normal Incidence)	$2\pi L^2 a/\lambda$
Small Airplane	200 sq. ft.
Large Airplane	800 sq. ft.
Small Cargo Ship	1500 sq. ft.
Large Cargo Ship	160,000 sq. ft.

if two targets are spaced less than one-half of the pulse length apart, the reflected echoes overlap, giving the effect of a single target.[7] When the targets are separated by more than one-half of the pulse length apart, no overlapping occurs and the targets appear individual of each other. A review of this discussion shows that a radar set should have a short pulse length if it is required to have high resolving power. The measurement of the dimensions of convective cells frequently places restrictions on the minimum permissible resolving power of meteorological radars. Since radio waves travel at 300 million meters per second in free space, in one microsecond a wave train would advance 300 meters. If such a pulse length were employed, the resolving power would be 150 meters. Targets would have to be at least 150 meters or 492 feet apart to be separately identified. As this may represent an appreciable distance under some circumstances, it has been found necessary

7 U. S. A. F., AF Manual 105-30, op. cit., pp. 6-7.

to reduce the pulse length to 0.5 microseconds for specialized purposes. Radars have been designed with pulse widths as short as 0.1 microseconds, with a consequent resolving power of 15 meters or 49.2 feet.

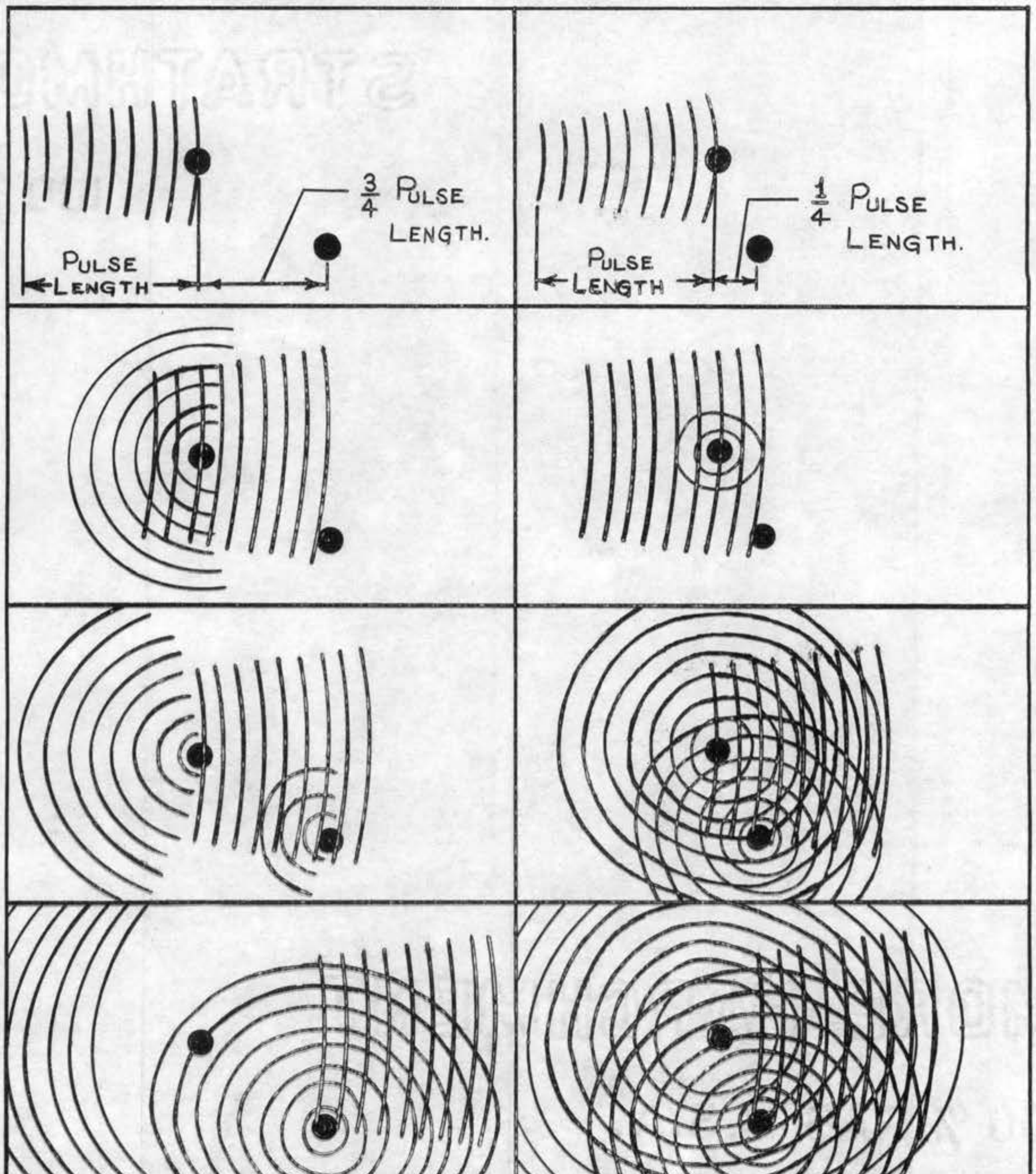

Fig. 3. Targets separated by more than one-half pulse length produce echoes which do not overlap.

Fig. 4. Targets separated by less than one-half pulse length produce overlapping echoes.

The type of resolution discussed above is called range resolution to distinguish it from horizontal and vertical resolution. The latter types are dependent upon the horizontal and vertical beam widths, respectively. All radar beams exhibit a slight amount of divergence[8] as the wave travels from the radiator into space. The angle of divergence between the half power points of the beam is defined as the beam width. For many applications this spreading effect is undesirable, because in addition to limiting the resolution the energy density of the wave front (watts per unit area) is decreased inversely as the square of the distance.[9] Consequently the energy incident upon any target is less than it would be were there no divergence. Thus beam spreading has the effect of limiting the range for a given transmitted power.

For certain purposes[10] it has been found desirable to maintain a high degree of horizontal resolution, but to decrease the vertical resolution. AN/APQ-13, an X-band radar designed for search, navigation and high altitude bombing, has a 3^{o} beam width in the horizontal plane, but a 90^{o} beam width in the vertical plane. This arrangement facilitates rapid interception, since moving targets can be more readily detected than if the vertical beam width were only 3^{o} also. Provisions are available, however, for adjusting the radiator so that both the

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8 U. S. A. F., AF Manual 105-30, op. cit., pp. 4-5.

9 Ibid., p. 4.

10 Ibid., p. 67.

vertical and horizontal beam widths are approximately 3°. This alteration is recommended when this radar is used in meteorological work. Other radars, such as AN/CPS-4 (Beavertail), AN/CPS-6 (V-Beam), and AN/TPS-10 (Lil Abner), which are intended for height finder purposes, have beam widths of 1° in the vertical plane, but fairly wide beam dispersions in the horizontal plane. This configuration allows targets to be detected through large azimuth angles very rapidly. Simultaneously, the height can be determined to a high degree of accuracy. When used in conjunction with other radars possessing good horizontal resolution, this equipment constitutes the heart of the fire control system.

From the standpoint of meteorology, vertical resolution is more important than horizontal resolution. This is because high resolving power in the vertical plane is necessary to accurately measure the growth rate and tops of convective cells. Also most storms have greater horizontal than vertical development. This is consistent with the statement in Chapter I that at maturity the horizontal and vertical dimensions of a convective cell are comparable. It is relatively infrequent that a storm is composed of only one convective cell. More commonly, as many as four or five cells may be present in a well developed thunderstorm. Fig. 5 shows the effect of vertical resolution upon the portion of the target intercepted. It can be seen at long ranges that the lower portion of the target is not detected due to the curvature of the earth. Spreading causes a vacant region between the cloud top and the upper limit of the beam at this range. Much useful energy may be lost in the upper portion of the beam.

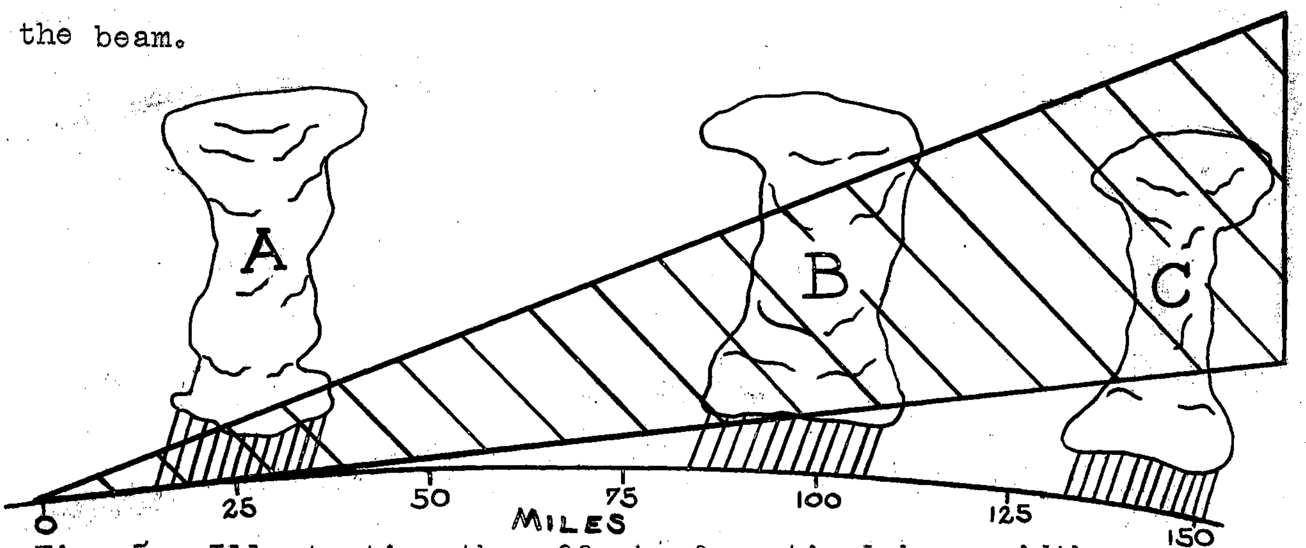

Fig. 5. Illustrating the effect of vertical beam width upon portion of target intercepted.

Since radar waves travel in straight lines and are not reflected by the ionisphere, it would seem reasonable to conclude that such propagation is limited to line of sight ranges. However radars operating on the ground have been known to detect objects far beyond the visual range, and in fact, beyond the horizon. In other instances, aircraft flying at very high altitudes have been able to increase the line of sight to ranges, which in some instances, exceeded the capabilities of the existing airborne radar. For example, aircraft such as the B-36 are capable of flying at altitudes approaching 50,000 feet. Neglecting refraction effects, the line of sight distance to the horizon is approximately,

$$R = \sqrt{2\ h} = \sqrt{2 \times 50{,}000} \text{ miles} = 316 \text{ miles.}$$

In the above relation the altitude, h, is given in feet. Only very few of the largest microwave early warning, MEW, radars are known to have ranges of this order of magnitude, and none of the airborne units. Evidently other factors than the mere specification of the optical horizon influence the range of a radar set. One factor; e.g., spreading of the beam, has already been considered as a potential means of limiting the range. The remaining factors will now be considered in detail.

The selection of the pulse recurrence frequency will have a definite bearing upon the range. For high pulse recurrence rates more energy is transmitted per unit time, assuming all other factors remain unchanged, but the time allowed for returning signals will be directly reduced. Therefore, the higher the pulse recurrence frequency, the shorter the range. The pulse recurrence rate also influences the required screen persistency of the scope. If the p.r.f. is relatively low, the target will be traced fewer times per second than if it is high. Moreover, if the scope is a PPI, the same portion of the scope may be traced only once every 30 seconds, or even less frequently. This requires that plan position indicators and scopes for long range radars should have high persistency. Likewise short range radars should have low persistency. It is general practice also to provide a sweep range which is greater than the associated equipment for any given setting. This is usually done to make full use of the existing range of the set. The SCR-584 is an exception[11] to this rule, however. As a result, certain difficulties such as "second sweep echoes" arise in the operation of this radar. This will be considered in detail in the next

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11 Ibid., p. 13.

chapter.

Another factor which may seem incidental but which is, nevertheless, important in limiting the range of a radar set is the rotational speed of the radiating system. The rotational speed must be slow enough to allow a signal to reach and return from a target at the most distant equipment range. Should it revolve too rapidly it may completely miss echoes returning from long ranges. This factor also influences scope persistency, because the slower the radiator revolves the longer is the period between successive retracings of the same portion of the screen.

Another factor which acts to limit the range is the receiver band width. The maximum range is determined by the minimum detectable signal.[12] The required amount of this signal will be dependent upon inherent equipment noise. The wider the band of the receiver, the greater will be the internal noise, and, consequently, the greater will be the required signal strength of the returning echo. Hence, the greater the band width, the shorter the maximum range. This gives rise to conflicting requirements, however, since a wide band width is necessary to pass the high frequency components of the echo which are necessary for good target definition.

Wexler[13] has made a study of the required power and wave-

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12 Ibid., p. 13.

13 Raymond Wexler and Donald M. Swingle, "Radar Storm Detection," Bulletin American Meteorological Society, XXVIII (April, 1947), pp. 159-167.

length necessary to procure a given radar range. The following mathematical development is based on his work. The power radiated per unit area from a non-directional or isotropic system is,

Power Density = Power Per Unit Area = $\left[\frac{P}{4\pi r^2}\right]$ Watts/Sq. Meter, where P is the transmitted power in watts, and r is the range to target in meters.

The denominator of the above expression will be recognized as the surface area of a sphere. This relationship clearly shows that spreading of the radiated energy reduces the power density in the wave front in proportion to the square of the radius of a hypothetical sphere corresponding to the range r. If the beam is focused by an appropriate reflecting device so that it has a gain G over the isotropic radiator, the power density now incident upon the target is,

$$\text{Power Density} = \left[\frac{GP}{4\pi r^2}\right].$$

Assuming isotropic reflection of the echo by the target, the power density arriving at the radar receiver is,

$$\text{Power Density} = \left[\frac{TGP}{(4\pi r^2)^2}\right]$$

where T is the effective target area. If the effective area of the radar receiving antenna is A, the power received will be

$$P_r = \left[\frac{ATPG}{(4\pi r^2)^2}\right].$$

It has been shown that,[14]

$$G = \left[\frac{4\pi A}{\lambda^2}\right]$$

where λ is the wavelength of radiation. Also, it has been determined empirically that the effective area, A, is approximately

$$A = \left[\frac{2}{3} B\right]$$

where B is the apertural area of the radiator. Substituting the two foregoing relationships into the expression for the power received yields

$$P_r = \left[\frac{TPB^2}{9\pi r^4 \lambda^2}\right] . \qquad (1)$$

Equation (1) shows that when the target does not completely intercept the radar beam, i.e., when the cross section of the target is much smaller than the beam, the received power is proportional to the inverse four power of the range and the inverse square of the wavelength. Referring to Fig. 5., this corresponds to the power received from a target of the approximate range and dimension as at point C.

The expression for the received power will now be developed for the case where the target just completely intercepts the beam. In Fig. 5. this would correspond approximately to the target at point B. Stratton has shown[15] that when the drop

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14 See Appendix A.

15 J.A. Stratton, "The Effect of Rain and Fog on the Propagation of Very Short Radio Waves," Proceedings of the Institute of Radio Engineers, XVIII (June, 1930), pp. 1064-1074.

diameter is much less than the wavelength, the scattering of radio energy is given by,

$$S = \left[\frac{2\pi^3 \rho^2 c}{\lambda^4 \quad r^2}\right]$$

where c is the velocity of light in free space, and ρ is the dipole moment of the drop.

The dipole moment for a single drop is equal to

$$\rho = \left[\left(\frac{e-1}{e+2}\right) a_i^3 \, E\right]$$

where e is the dielectric constant of the water,

a_i is the drop radius, and

E is the electric field intensity acting on the dipole.

The incident power density, P_i , is equal to

$$P_i = \left[\frac{cE^2}{8\pi}\right] .$$

When the above two relationships are substituted into the scattering equation, the resulting expression becomes

$$S = \left[\left(\frac{16\pi^4 P_i a_i^6}{\lambda^4 \, r^2}\right) \cdot \left(\frac{e-1}{e+2}\right)^2\right] .$$

The radar cross section has previously been defined and is given by the following equation,

$$\sigma = \left[\frac{4\pi r^2 S}{P_i}\right] = \left[\left(\frac{4\pi r^2}{P_i}\right) \cdot \left(\frac{16\pi^4 P_i a_i^6}{\lambda^4 \, r^2}\right) \cdot \left(\frac{e-1}{e+2}\right)^2\right] = \left[\left(\frac{64\pi^5 a_i^6}{\lambda^4}\right)\left(\frac{e-1}{e+2}\right)^2\right] .$$

If there are n targets which intercept the beam, and if these targets are at such positions that their individual echoes arrive at the radar receiver at the same instant, although the phase relationships may be variable, the power in each echo may be added arithmetically. The effective target area then becomes,

$$T = \left[\left(\frac{64\pi^5}{\lambda^4}\right)\left(\frac{e-1}{e+2}\right)^2\right] \sum_{i=o}^{n} a_i^6 . \qquad (2)$$

Equation (2) is the mathematical expression for the well known "Rayleigh Law" of scattering. Originally, Rayleigh used a similar line of reasoning in explaining that the blue color of the sky is due to scattering of sunlight by dust particles. Expressed in words, this law states that the scattering cross section is proportional to the sixth power of the drop radius and the inverse fourth power of the wavelength. This relationship has been verified mathematically for 10-cm waves for all rainfall intensities. For 3-cm waves this relationship holds for rainfall intensities up to 25 millimeters per hour. If the value of T obtained from equation (2) is substituted back into equation (1), the power received becomes

$$P_r = \left[\left(\frac{64\pi^4 PB^2}{9r^4 \lambda^6}\right)\left(\frac{e-1}{e+2}\right)^2\right] \sum_{i=o}^{n} a_i^6 .$$

If the above equation is summed from zero to $\underline{n}$, and if the mean sixth power of all the drops illuminated is substituted for $\underline{a_i^6}$, the above becomes

$$P_r = \left[\left(\frac{64\pi^4 PB^2 n a^6}{9r^4 \lambda^6}\right)\left(\frac{e-1}{e+2}\right)^2\right]$$

where $\underline{n}$ is the number of drops illuminated, and

$\underline{a}^6$ is the mean sixth power of radii of all drops illuminated.

Next, the following substitution is introduced:

$$n = NV$$

where N is the drops per unit volume, and

V is the volume effectively illuminated.

If the target completely intercepts the beam as at position B in Fig. 5., the maximum volume which is effectively illuminated, V_m, may be shown to be one-half the pulse length in space times the area illuminated by the antenna beam. This gives

$$V_m = \left[\left(\frac{\pi r^2 \theta^2}{4}\right)\left(\frac{d}{2}\right)\right] = \left[\frac{d\pi r^2 \theta^2}{8}\right]$$

where d is the pulse length in space,

and θ is the angle of beam width in radians.

Furthermore, it has been empirically demonstrated that[16]

$$\theta = \left[\frac{0.85\lambda}{D}\right]$$

where D is the diameter of the paraboloid in meters when λ is expressed in meters. The aperture area of the parabola is related to the diameter by the following expression:

$$B = \left[\frac{\pi D^2}{4}\right]$$

Substituting this expression into the previous one and squaring yields

$$\theta^2 = \left[\frac{0.85\lambda}{D}\right]^2 = \left[\frac{(0.85\lambda)^2}{\left(\frac{4B}{\pi}\right)}\right] = \left[\frac{(0.85\lambda)^2\pi}{4B}\right].$$

When the equations for n, V_m, and θ^2 are substituted into the power received equation, the result is

$$P_r = \left[\left(\frac{0.16\pi^6 BdNa^6 P}{r^2 \lambda^4}\right)\left(\frac{e-1}{e+2}\right)^2\right].$$

If the target completely intercepts the beam and some unilluminated volume remains, the above expression must be

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16 Wexler and Swingle, *op. cit.*, p. 161.

modified by the percentage of the maximum volume that is completely intercepted, thus,

$$P_r = \left[\left(\frac{0.16\pi^6 BdNa^6 P}{r^2 \lambda^4}\right)\left(\frac{e-1}{e+2}\right)^2 \left(\frac{V}{V_m}\right)\right]. \quad (3)$$

The above expression holds for targets at any range, up to the range at which V is just equal to V_m. In Fig. 5., this would correspond to positions A and B.

The foregoing results show that: (1) Targets whose echoing area are equal to or larger than the beam cross section give rise to a received power which is inversely proportional to the square of the range and the fourth power of the wavelength. This is due to the fact that up to the range at which the beam cross section just exceeds that of the target, the total power incident upon the object is constant. However, the energy scattered backwards from the echo source is not directive like the transmitted beam. Its radiation pattern varies between a directivity approaching that of the transmitted beam and isotropic conditions. The exact pattern will be controlled by the shape of the echo source, its uniformity, and the angle of incidence of the transmitted beam. As a result, an attenuation factor of $1/r^2$ is always introduced along the return path. There is an exception to this condition in which the echo source has the same directivity as the beam. Such a condition arises when using the so called "echo box" frequently employed for tuning radar sets. This is merely an antenna mounted at the center of a parabolic reflector and placed on a line with the radar antenna. The spacing of the antenna and echo box is commonly 20 to 50 feet. Most echo boxes include a delay line provision so that the target appearing on the scope has an apparent range of 10 to 20 miles. This facilitates tuning by moving the echo away from the bright spot at the center of the PPI. Such a highly directive target is so infrequently encountered in meteorological work that its smaller range attenuation factor may be disregarded. (2) Targets whose echoing areas are smaller than the beam cross section give rise to a received power which is inversely proportional to the fourth power of the range and the square of the wavelength. As stated previously, the power falling upon the target under these conditions is inversely proportional to the square of the range. The overall attenuation factor is the product of the transmission path attenuation factor and the echo path attenuation factor. This would produce a transmission attenuation factor of $1/r^2$ and also an echo attenuation factor of $1/r^2$. The overall attenuation factor would be the product of the two or $1/r^4$.

Due to the relatively gradual diverging effect, no sharp transition occurs for the two conditions above. Moreover, the above results are based on the premise of absolutely uniform target cross sections. Well developed thunderheads will have a heteorogeneous mixture of ice, hail, and water, all of which have different reflectivity constants. Therefore these conclusions should only be regarded as approximate.

Other writings[17] have indicated that when the target is

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17 U.S.A.F., AF Manual 105-30, op. cit., p. 10.

larger than the beam in one dimension but not the other, the received power will be inversely proportional to the cube of the range. This is perhaps the condition which is most frequently encountered when tracking storms at long ranges. Generally several convective cells of about the same vertical development will group together in moderate to severe thunderstorms. Under such conditions the horizontal dimension of the storm will exceed the horizontal beam width, but the vertical dimension of the beam will exceed the vertical convective cell development.

Equation (3) shows that to have a large received power, and therefore greater range capabilities, a radar should have a high peak of transmitted power, a large and well focused radiating system, a short wavelength, and a long pulse width. The last requirement appears to be in conflict with the short pulse width required for high range resolution. However, inspection of (3) shows that the product of the transmitted power and the pulse length, Pd, appears as a factor. It is known that

$$d = ct$$

where c is the velocity of light and t is time. In addition, energy is given by

$$W = \int_0^t P\, dt.$$

If the power is considered constant over the pulse period, and this assumption holds approximately for most radars, the preceding expression becomes

$$W = Pt.$$

Therefore the product becomes

$$Pd = P(ct) = cPt = cW.$$

Since c is a constant, it may be multiplied by the remaining numerator factor. This gives two new factors, one of which is a constant and the other the expression for the energy contained in each transmitted pulse. Since the energy may be computed from the area under the power versus time curve, it is evident that the energy, and hence the received power, will be invariant provided the area under the curve is constant. This can be achieved by using a small transmitted power and a long pulse period, or a very large transmitted power and a very short pulse width. These conditions are demonstrated in Fig. 6. The pulse at (A) has twice the period and half the power of the pulse at (B).

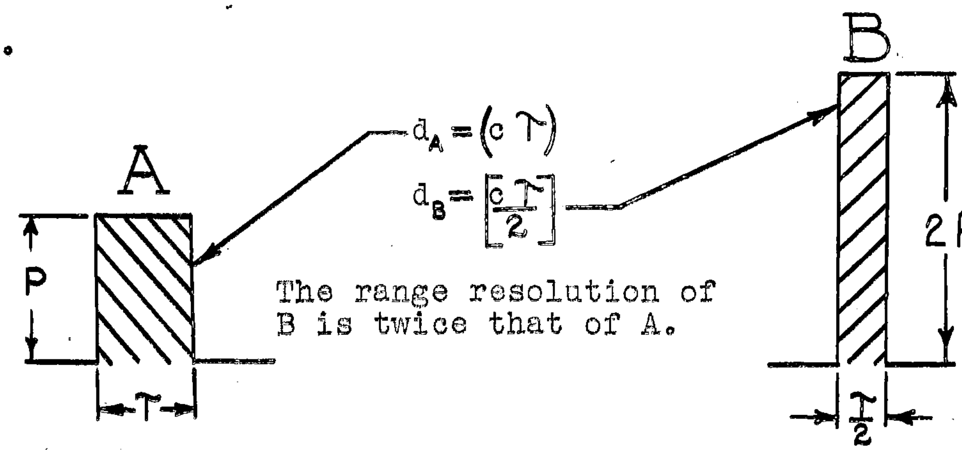

Fig. 6. Illustrating the power versus range resolution relationship.

Although the area under both curves, and therefore the energy in each pulse is the same, the range resolution of the pulse at (B) is twice as great as at (A). In view of this consideration, the previous requirements should be modified to include a short pulse width and a large amount of energy per pulse. This is equivalent to specifying a very high peak power.

Equations (2) and (3) show that the radar cross section of a target is proportional to Na^6, where N is the total number of

Table III. Median Drop Diameters and Na^6 for Clouds and Rain.

Cloud Type	Median Diameter	Na^6 (cm^3)
Altostratus	9.0 μ	2.70×10^{-17}
Nimbostratus	9.1 μ	14.79×10^{-17}
Stratocumulus	6.3 μ	9.90×10^{-17}
Cumulus	6.4 μ	6.13×10^{-17}
Stratus	15.4 μ	8.57×10^{-17}
Light Rain (1.25 mm/hr)	1.30 mm	0.07×10^{-10}
Moderate Rain (5 mm/hr)	1.65 mm	0.70×10^{-10}
Heavy Rain (12.5 mm/hr)	1.95 mm	2.20×10^{-10}
	($1\ \mu = 10^{-4}$ cm)	

drops per unit volume, and a is the root mean sixth power of the drop radius. Table III, taken from Wexler,[18] gives median diameters for various clouds and rain. It may be seen that Na^6 for moderate rain is approximately one million times greater than that of clouds. This leads to the conclusion that moderate rain at 100 miles would give a greater return than clouds at 1/10 mile. Most clouds are generally not detectable by radar, although some which precede the onset of a rainstorm do give a return , though rain may not be visibly falling. Wexler believes that under these circumstances the drops in the clouds approach the size of raindrops.[19] If this be the case, radar would be useful in determining qualitatively those clouds from which rain might be expected.

Snowflakes have a mean diameter of about 1.5 cm as compared with raindrops, whose mean diameter is approximately 1.5 mm.

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18 Wexler and Swingle, op. cit., pp. 159-167.

19 Wexler and Swingle, loc. cit.

However, the reflectivity of snow and ice is much less than water, because of the smaller dielectric constant of the former. This has led to some difficulty in determining the radar cross section of snow by comparison tests with water. As a result no quantitative estimate of the radar cross section is available for snow and ice. These results are supported by the fact that portions of the cloud containing large amounts of ice are frequently not detectable except at very short ranges from the radar. This gives the impression that the cloud increases in size as it approaches the radar, and decreases as it recedes. Actually the highly reflective portions containing water are the first to be detected and the last to fade. The less reflective portions are only detectable in the immediate vicinity of the station.

The foregoing mathematical relationships, and the subsequent conclusions based upon them, were developed by assuming negligible attenuation of the wave. In practice it is found that under certain circumstances atmospheric attenuation may be appreciable. Wexler observed a storm[20] approaching the United States Army Signal Corps Laboratories, Belmar, New Jersey, on the night of April 2, 1946. Heavy rain was visible on the 3-cm radar set used to a range of 70 miles, but attenuation was so severe that the sharp outline of the cold front was detectable to a range of only 30 miles.

As electromagnetic waves travel through the atmosphere,

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20 Ibid., pp. 159-167.

they are attenuated by scattering and absorption.[21] For particles large in relation to the wavelength and of heavy concentration, scattering results in appreciable attenuation of the incident wave. Also precipitation particles are characterized by a relatively higher dielectric loss, and therefore absorb energy from the passing wave by converting it into heat. Both of these effects are unimportant for wavelengths exceeding 10 cm, but **they may** appreciably limit the range of 1 cm waves, or shorter. Stratton[22] was one of the first to recognize this effect. Attenuation also results from absorption by oxygen and uncondensed water vapor. The mechanism[23] involved in this effect, however, is different from the absorption by precipitation particles.

A strong absorption band occurs near 0.5 cm for oxygen. Likewise, a strong absorption band for water vapor has been calculated to be centered near 1.33 cm. It is believed also that a weaker absorption band for water vapor occurs near 0.17 cm. The most important thing to be gained from these studies is that atmospheric attenuation increases with decreasing wavelength, becoming a major consideration for radiation below 1 cm. The following table has been taken from Wexler[24] to illustrate

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21 Donald E. Kerr, Propagation of Short Radio Waves, pp. 22-27.

22 Stratton, loc. cit.

23 Kerr, loc. cit.

24 Wexler, loc. cit.

Table IV. Percentage Two-Way Transmission For 3.2 Cm and 10 Cm Radar Through A Tropical Atmosphere.

Range	3.2 Cm Waves	10 Cm Waves
50 km	71.6 %	84.8 %
100 km	52.2 %	72.3 %
200 km	32.7 %	55.6 %
300 km	25.6 %	47.3 %

attenuation through a tropical atmosphere for two-way transmission.

In view of the foregoing considerations, equation (3) can be written in its most general form[25] to consider the effects of attenuation as follows:

$$P_r = \left[\left(\frac{0.16\pi^6 BPdVna^6}{r^2 \lambda^4 V_m}\right)\left(\frac{e-1}{e+2}\right)^2\right] \times 10^{-0.2Kr} \qquad (4)$$

where K is the atmospheric attenuation constant. In the case of propagation through heavy rain, a different attenuation constant would have to be employed.

Although transmission of 3.2 cm waves through moderate or heavy rain is greatly attenuated, it seldom happens that such rainfall intensities occur for more than a few kilometers. A notable exception to this situation is present along frontal zones or under certain orographic circumstances that give rise to extensive areas of heavy rain. Waves in the 3 cm band are virtually blacked out by such exigencies.

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25 Raymond Wexler, "Radar Detection of a Frontal Storm 18 June 1946," Journal of Meteorology, IV (January, 1947), pp. 38-44.

When the attenuation due to rain and atmospheric effects are considered, it is found that for 3.2 cm radar moderate rain produces a stronger echo than light rain up to 75 kilometers due to larger values of Na^6 for moderate rain. Beyond 75 kilometers increased rain attenuation favors the reception of light rain. Likewise, heavy rain produces a stronger echo for 3.2 cm waves below 10 kilometers, and less at greater distances. It has been estimated that if the minimum detectable signal of the radar were

$$P_r = P \times 10^{-15}$$

then 3.2 cm waves could detect light rain <u>through light rain</u> to about 50 kilometers; moderate rain could be detected <u>through moderate rain</u> to about 65 kilometers; and heavy rain could be detected <u>through heavy rain</u> to about 25 kilometers.

When 3.2 cm waves are compared to 10 cm waves, it is found that the shorter wavelength gives the better return from heavy rain <u>through heavy rain</u> up to approximately 41 kilometers. Beyond this range, 10 cm waves give a stronger echo. Echoes from moderate rain <u>through moderate rain</u> give a better return for 3.2 cm waves up to approximately 124 kilometers. At greater ranges 10 cm waves give a stronger echo. These comparisons are made on the basis of equal radar characteristics for both sets.

Equation (3) shows that in the absence of rain attenuation the power returned for 3.2 cm waves is approximately 100 times greater than from 10 cm waves. The conclusion may then be drawn that while 10 cm waves are more suitable for storm detection through appreciable distances of heavy rain, 3.2 cm waves are better for the temperate latitudes, where in general moderate and light rain prevail. Heavy rain does not frequently exist over long ranges in this region.

It was mentioned earlier in this chapter that under certain circumstances radar waves have been known to detect targets considerably beyond the horizon. This point will now be considered in detail. Generally speaking, the index of refraction even under standard conditions decreases slightly with increasing altitude. Long waves such as those used in the broadcast band are not appreciably influenced by this condition. However as the wavelength of radiation is steadily reduced a refraction effect is noted. As the wavelength decreases below one meter, the effect is sufficiently large that it must be taken into consideration in determining the radar horizon.

For average weather conditions the curvature of the waves is less than that of the earth, and the horizon distance is increased by approximately 15 %. "Coverage diagrams" of the radar beam may be constructed by drawing the ray path as a straight line and increasing the earth's radius by a factor of 4/3. The diagrams or charts are useful for predicting those portions of space which may be reached by the radar.

In unusual situations the radar waves will travel for appreciable distances beyond the horizon. This phenomena is explained by the presence of trapping layers or ducts.[26] These ducts are caused by an extremely rapid decrease of index of refraction with height. They form in the lowest 2000 feet of the

26 Kerr, op. cit., p. 9.

troposphere and are generally about 200 feet deep. The principal meteorological factors responsible for duct formation are an abnormal moisture lapse or decrease of water vapor content with altitude,[27] together with a pronounced temperature inversion or increase of temperature with altitude. The mathematical analysis of this phenomena has been developed in detail by the members of the Radiation Laboratory, M.I.T.[28] Fig. 7 shows that

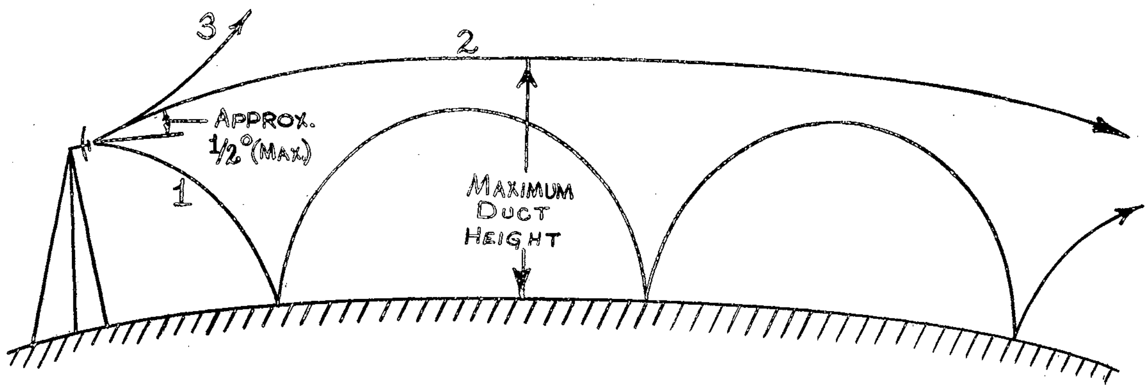

Fig. 7. Guided propagation of short radio waves.

the path of the rays are very similar to the type of propagation experienced in wave guides. Recognition of this fact has led to the name "guided propagation" for these anomalous conditions. The rapid variation of index of refraction does in fact cause these ducts to behave similar to wave guides, but the wave is gradually bent rather than sharply reflected. Waves leaving the antenna along path 1 bounce as shown in the figure. Those leaving at angles up to or less than path 2 also bounce. Those leaving exactly along path 2 travel around the upper edge of the

27 Richard D. Coons, "Guided Propagation of Radar in Thunderstorm Conditions," Bulletin American Meteorological Society, XXVIII (September, 1947), pp. 324-329.

28 Kerr, loc. cit.

duct. Those exceeding the angle of path 2 penetrate the duct and travel in space in the conventional manner. The minimum angle which just permits the wave to leave the duct is called the penetration angle. This angle is generally less than 1/2° under most circumstances.[29]

On the east coast near the New York, New Jersey, Massachusetts area, July through October is the most favorable period for duct formation.[30] Wexler[31] has noted that in the Summer of 1945, 3 cm radar detected storms up to 200 miles in New Jersey, while the normal range of the radar was only 75 miles. Other reports[32] indicate that radar beacons were detected 500 miles away by aircraft flying below 6000 feet. Echoes from Arabia were received at Bombay, India,[33] a distance of 1700 miles. When corroborated with other verifying facts, these records substantiate the conclusion that the attenuation is noticeably reduced. Of course it is clear that this trapping tends to confine the vertical extent of the beam and thereby reduce a large proportion of attenuation. Ordinarily both the radar and the target must be in the duct to obtain an echo. However, since these trapping layers are generally not perfect in restricting the beam, a small amount of "leakage" occurs and

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29 U.S.A.F., A.F. Manual 105-30, op. cit., p. 12.

30 Kerr, op. cit., p. 11.

31 Wexler and Swingle, op. cit., pp. 159-167.

32 Kerr, loc. cit.

33 Ibid., p. 9.

targets or radars situated near such layers may experience unusually long ranges.

Having considered the major aspects of radar in detail, it is now possible to prescribe the requirements of a meteorological radar most suited to studies of tornado formation and development. The results are summarized as follows:

1. Wavelength - 3.2 centimeters.
2. Pulse Recurrence Frequency - This factor must be set by the operating range of the radar.
3. Peak Power - As high as possible; preferably greater than 50 kilowatts.
4. Pulse Period - 1 microsecond or less.
5. Beam Width - Both the horizontal and vertical beam widths should not exceed 2° for best results.
6. Range - The equipment should have a maximum range of 150 to 200 miles if possible. However, a maximum equipment range of 75 to 100 miles is in common use and is suitable for meteorological work.
7. Receiver Sensitivity - The receiver sensitivity should be sufficient to detect targets at the maximum range, and should have a band width capable of providing a reasonable degree of target definition. The inherent

noise should not be so great as to seriously limit the range by requiring an unusually high echo power.

8. Data Presentation - The use of a PPI, A-Scope (and expanded A-scope if possible), and RHI are strongly recommended for tornado tracking.

9. Radiator Motion - The radiating device should have a full 360° azimuth motion and 0° to 90° vertical motion.

10. General Equipment Types - At this writing no one radar is known to meet all of the foregoing requirements. It is therefore recommended that a combination of two radars be employed. One should be of the general search and navigation type radar employing the PPI and A-scopes. The second radar should be of the height finder type employing the range height indicator scope.

The United States Air Force[34] lists a number of radars

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34 U.S.A.F., A.F. Manual 105-30, pp. 63-67.

suitable for storm detection. These are divided into three major installation categories:

I. Fixed Installations.

1. AN/CPS-1 (MEW). This is Microwave Early Warning radar having a peak power of 750 kilowatts, a horizontal beam width of 1° and a vertical beam width of 2.5°. The frequency is in the S-band and the range is 100 miles for medium bombers and 200 miles for thunderstorms. Complete coverage of 360° of azimuth is provided.

2. AN/CPS-4 (Beavertail). This is an S-band height finding radar with a peak power of 750 kilowatts. The horizontal beam width is 5° and the vertical beam width is 1°.

3. AN/CPS-6 (V-beam). This is an S-band search set with a peak power of 750 kilowatts. The equipment employs two beams separated from each other by 45° for measuring height. Each beam has a width of 1°.

4. SCR-615-B. This is an S-band search and Ground Controlled Interceptor equipment with a peak power of 750 kilowatts. The beam width is 3° and the entire radiation lobe is revolved through a 4° cone at 1380 rpm to increase vertical coverage. The beam may be held stationary if desired. The radiator revolves through 360° azimuth at 6 rpm.

II. Mobile Radar Sets.

1. SCR-584. This is an S-band search and automatic tracking radar. The peak power is 250 kilowatts and the

range is 96,000 yards. The entire unit is mounted on a 10-ton trailer. The pulse length is 0.8 microseconds, and the pulse repetition frequency is 1707 cycles. The data is displayed on a J-scope, expanded J-scope, and a plan position indicator. The equipment employs a 4° beam width, the axis of which is offset 1.5° from the focal axis of the parabola. The antenna spins at 1800 rpm generating a 3° cone. The radiator rotates through 360° azimuth, and 0° to 90° elevation.

2. AN/TPL-1. This is an S-band radar set designed for search light control. It has a peak power of 125 kilowatts and a 7° conical beam. The equipment has a range of 60,000 yards and employs a PPI scope. This equipment is suitable for upper wind observations as well as storm detection.

3. AN/TPS-10 (Lil Abner). This is an X-band search set with a peak power of 80 kilowatts. It employs an RHI scope and may be used for determining growth rates and vertical dimensions of convective cells.

III. Airborne Radar Sets.

1. SCR-717-B. This is an S-band set with a 10° conical beam and a peak power of 100 kilowatts. Provisions are available for reducing the beam width to 5° by replacing the 29-inch diameter paraboloid by a 60-inch paraboloid. The data is presented on the plan position indicator.

2. AN/APQ-13. This set is a high altitude bombing and navigation X-band set. The peak power is 35 kilowatts

and range for thunderstorms is 150 miles. The radiation pattern is a "cosecant-squared" beam. The horizontal beam width is 3° and the vertical beam width is 90°. For meteorological applications adjustments can be made on the radiator to produce a 3° vertical beam width.

3. AN/APS-15. The military and electrical characteristics of this equipment are identical with those of AN/APQ-13, but all component parts are not interchangeable.

In the next chapter, the appearance of meteorological echoes on various types of radars will be discussed.

CHAPTER IV

RADAR PICTURIZATION OF METEOROLOGICAL PHENOMENA

A review of the literature relating to the employment of radar in the meteorological field reveals that certain types of weather produce characteristic echoes. For example, the Dow Chemical Company[1] has found that radar is a very successful device for tracking the path of hurricanes in surrounding regions. The armed services and private research institutions have been able to identify various types of thunderstorms and precipitation areas by their returns. In fact, radar meteorology was able to come into existence only because storms and hurricanes gave consistently similar responses on the indicator. Originally the term "cloud echoes" was used to describe these meteorological reflections.[2] The more accurate name, "precipitation echoes", is now coming into general use as studies indicate that almost without exception precipitation is present in the echo source.[3]

There are a number of characteristics which aid in the identification of precipitation echoes. It is to be understood, however, that the most important factor in establishing the origin of radar returns is well trained and adequately

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1 R. C. Jorgensen and W. F. Gerdes, "The Dow Chemical Company Leads Industry in Using Radar for Hurricane Detection," Bulletin American Meteorological Society, XXXII (June, 1951), pp. 221-224.

2 Kerr, op. cit., p. 621.

3 U.S.A.F., A.F. Manual 105-30, op. cit., p. 14.

experienced operators. Even then there are certain situations which arise to prevent the positive recognition of responses. When precipitation echoes are observed they are frequently intermingled with fixed ground targets, aircraft, or ships at sea. Echoes of the type arising from severe thunderstorms have the effect of "blanketing" such smaller objects in the same region. Furthermore, the tin foil used for radar jamming, frequently referred to as "window", has given returns which on occasions could easily be mistaken for precipitation echoes.[4] The areas above extensive forest fires have also been known to produce scope returns.[5] In spite of these apparent difficulties, the following features will be found helpful in storm recognition:

1. Motion. Precipitation echoes show horizontal motion with respect to the terrain below. The limits of the velocities observed have been found to vary from zero to 100 miles per hour. These speeds were found to agree with weather reports of winds aloft. Numerous experiences have shown that radar is a most effective device for determining upper winds during conditions of heavy overcast. This property of radar is valuable not only for differentiating fixed and moving targets but also for predicting the arrival time of a storm.

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4 _Ibid._, p. 17.

5 _Ibid._, pp. 17-18, 44-45.

2. Size. Precipitation regions generally cover wide areas and are large in comparison to other targets. Under certain circumstances the entire PPI may be covered with returns. In other instances, small isolated thunderstorms may be difficult to distinguish from large cities. While thunderheads are capable of blanketing returns from large targets, cases arise where adjacent echoes make it difficult to differentiate the storm from a town. This might be particularly serious in the case of an aircraft employing radar navigation. Since the plane would have a velocity relative to both the thunderstorm and the city, both echoes would show motion on the scope.

3. Distance. Because of their extensive horizontal and vertical development, storm echoes may be detected at ranges greatly in excess of those for battleships or aircraft. Thunderstorms have been observed as far as 250 miles.

4. Altitude. Precipitation echoes have been received from the horizon level to altitudes approaching 60,000 ft. If the radar is on the ground, the antenna may be tilted upward to eliminate land targets. Radars employing the plan position indicator may be used to determine the height of a thunderstorm convective cell by increasing the antenna elevation until the target just fades. Radars using the range height indicator display the elevation of the target directly on the scope. From the foregoing it may be concluded that when large returns

are received from targets considerably above the horizon, the source is a precipitation echo. Furthermore, the echo intensity will become more intense as the angle of elevation is increased. However, for storms at exceptionally long ranges where cloud tops are just visible, increasing the elevation angle may result in a decrease of signal return.

5. Average Intensity. Precipitation echo intensities are quite variable. They may range from an indefinite lower limit bordering on the threshold level, to amplitudes sufficiently great to obliterate strong echoes from close land targets.

6. Brightness. The PPI presentation is controlled by a brilliance or intensity adjustment. As explained in the last chapter, the intensity is set so that the radial sweep just fades out with no incoming signal. Some precipitation returns, associated with light to moderate rain, have a typical cloudlike or transparent appearance. Others are sharply outlined and very bright. The exact setting of the intensity control to effect positive identification of received echoes can only be achieved through considerable experience.

7. Stratification. Precipitation echoes extending over large areas, such as those associated with nimbostratus clouds, show evidence of layer-like structures. Returns have been observed from as many as four such layers

simultaneously.[6] There may be a great variation in the characteristics of these layers, but under most circumstances these echoes are related to wide regions of general rain.

8. Intensity Fluctuation. Radar returns received from ground targets have relatively unvarying responses for short time intervals. Precipitation echoes, on the other hand, vary rapidly between subsequent sweeps of the indicator. This effect, in general, is not evident on the PPI or other intensity modulated scopes having long persistencies, but it becomes readily apparent when viewed on the A-scope. If the precipitation area is small in comparison to the sweep range, the echo appears as a "fuzzy bump" rising out of a thick base line. The base line has the thick appearance because of this rapid variation. In contrast, other land targets give fairly constant returns that break cleanly with the base line. When an attempt is made to analyze this echo in great detail, it is necessary to use the expanded A-scope. In fact, the most satisfactory indicator for identifying precipitation echoes is the expanded A-scope.[7] When photographs are taken of the expanded A-scope, the echo is observed to have a lacy or threadlike structure. Since, in addition, most photographs are taken for at

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6 Kerr, op. cit., p. 625.

7 Ibid., p. 624.

least several sweeps, the picture is a superposition of all returns arriving during the exposure. Observers indicate that a visual inspection gives the impression of a "dancing signal".

Radar records of meteorological phenomena have been utilized in the following ways:[8] (1) as a means of differentiating fixed and precipitation echoes; (2) as a means of distinguishing frozen precipitation from rain; (3) as a method of determining the velocity distribution of raindrops; (4) as a means of measuring the water vapor in cloud convective columns; and (5) as a means of studying the turbulence associated with precipitation areas. The first two and the fourth studies have been reasonably successful. Evidence which will be presented subsequently indicates that turbulence measurements may be effected through future research. However, neither drop side arrangement nor velocity distribution measurements have been developed reliably at this time. One investigator[9] arrives at quantitative results based upon certain assumptions regarding drop sizes which are restricted to limited situations. Additional work[10] has been conducted along these lines, but as yet no precise

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8 Arthur E. Bent, "Radar Detection of Precipitation," _Journal of Meteorology_, III (September, 1946), pp. 78-84.

9 Pauline M. Austin, "Measurement of Approximate Raindrop Size by Microwave Attenuation," _Journal of Meteorology_, IV (August, 1947), pp. 121-124.

10 J. S. Marshall, R. C. Langille, and W. Mck. Palmer, "Measurement of Rainfall by Radar," _Journal of Meteorology_, IV (December, 1947), pp. 186-192.

mathematical relationships can be established between drop size distribution and precipitation echoes. One Canadian[11] meteorologist has, however, verified a correlation between drop size and range for received echoes on a number of occasions. He has also attempted to establish an intensity criteria in terms of the radar range, but this has not been as successful as the former requirement. Finally, an attempt has been made to correlate radar reflectivity to liquid water content[12] of air, but the results have been largely speculative due to the widely varying droplet dimensions. While much interest has been displayed in striving for a quantitative analysis of hydrometeors by radar, it is apparent that additional research is necessary.

It will be recalled that in Chapter III the range equation, equation (3), was simplified into its final form by assuming an average drop size to be the mean of all of the drops illuminated. This type of approach has been employed by the investigators cited in the above paragraph. While it limits precise quantitative analysis of precipitation particles within clouds, it does aid visualization of the physical situation in a qualitative sense.

It has been observed that the strength of the radar echo is greater when the hydrometeors are water drops or rain, than when

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11 D. W. Perrie, "The Rain Required for a Radar Echo," Bulletin American Meteorological Society, XXX (October, 1949), pp. 278-281.

12 Pauline M. Austin and Harrie E. Foster, "Note on Comparison of Liquid Water Content of Air With Radar Reflectivity," Journal of Meteorology, II (April, 1950), p. 161.

they are snow or ice. Referring to equation (3) it is apparent that this should be the case, since the larger the dielectric constant, e, becomes, the more nearly the ratio $\left[\frac{e-1}{e+2}\right]^2$ approaches unity. Water is known to have a greater dielectric constant than snow or ice. Thus, a qualitative check is provided by field operations on the conclusion that the intensity of energy scattered backwards toward the radar is proportional to the mass of water per unit volume. It is also known[13] that larger water particles give a stronger return. The range equation is in agreement with this observation, since the received power increases as the sixth power of the drop radius. Consequently, for a given quantity of water per unit volume the back scattering increases with the mass of individual drops, and therefore, inversely with the total number of drops. The following example may serve to clarify this point. If 100 grams of water were broken into 1000 equal size drops evenly distributed throughout a given volume, roughly twice the echo strength could be expected as if the same 100 grams were divided into 2000 equal size drops and distributed throughout this same volume. While operating experiences such as these are in general agreement with theory, it is to be clearly understood that precise mathematical relationships have not been developed from such observations.

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13 U.S.A.F., A.F. Manual 105-30, _op. cit._, p. 6.

Another qualitative aid used by the military service[14] is an explanation of the rapid variation of precipitation echo intensity. It was shown that when targets are spaced more closely than one-half the pulse length the individual echoes overlap and the appearance on the radar-scope is as though there were only one target. Although it was not brought into the discussion in Chapter III, it is evident that the echoes will add constructively or destructively depending upon the relative positions of the two targets and the wavelength of the radiation. As an example, for a wavelength of 10 centimeters, a difference in path length of 2.5 centimeters would result in a relative phase shift between the two targets of 180°. If the wavelength were decreased to 3 centimeters, a path difference of only 0.75 centimeters would result in the same relative phase shift (180°). When it is realized that water, snow and ice are moving rapidly in the vertical convective column of thunderheads, and thus continuously changing position relative to adjacent forms of precipitation, the signal returning at one instant may be the constructive superposition of the majority of all echoes and hence very strong. A very short time later it may be a strong destructive addition with a resultant weak overall return. At still other times it may vary between these two extremes. In Fig. 8 below, a rough production is made of a few of a series of photographs taken by the Air Force.[15] The echo intensity was

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14 Ibid., p. 6.

15 Ibid., p. 8.

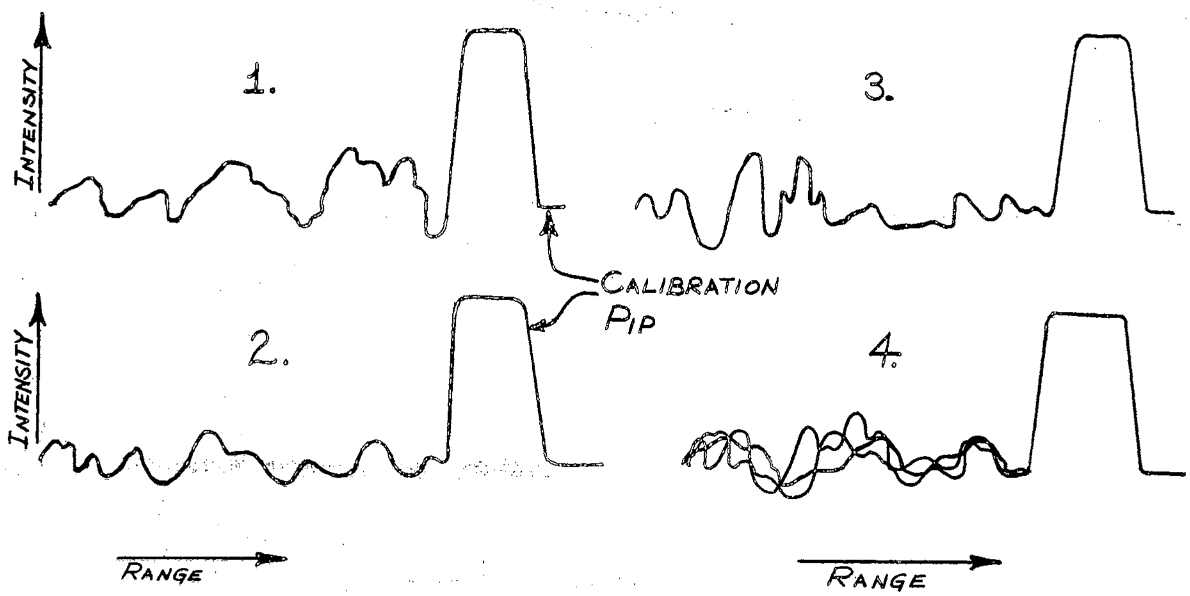

Fig. 8. Echo intensity fluctuation.

displayed on an A-scope. The calibration pip provides an approximation of the signal strength. These pictures were taken by a high speed motion picture camera. The successive photographs are numbered; e.g., 1, 2, 3. The interval between each picture is 0.003 seconds. The picture at 4 is a superposition of the first three, and is what would be visually observed. Since there is no resemblence between successive photographs, the fluctuations occur at a rate in excess of 1/0.003 or 333 cycles per second. The wavelength of the radar used for this observation was 10 centimeters. Experience indicates that the short wavelengths are more capable of detecting and indicating this rapid variation than very long wavelengths. This is easily understood when it is realized that the distance which a hydrometeor moves in a convective cell is a much greater proportion of the wavelength at the higher frequencies than at the lower ones. Consequently, the interference patterns are more evident at the short wavelengths. It should be realized that the J-scope may also be used for such observations. The low persistency of A and J-scopes compared to the intensity modulated types, and the intensity versus range plot make the A and J indicators well suited for this work (A and J-scopes are sometimes called "deflection modulated" indicators because amplitude is plotted versus range).

Ligda[16] has perfected a method of obtaining an echo from a lightning stroke. The radar antenna is directed toward the thunderhead and the elevation angle is increased until the average intensity of the precipitation echo is approximately one-half the saturation value. If the storm selected is severe, and if the radar is pointing toward the center of electrical activity, lightning stroke returns will be observed to rise out of the precipitation echoes quite abruptly. The echo intensity from a high current stroke may be expected to reach the saturation level. This signal will differ from the sferic type of return. Whereas the sferic may give high intensity all along the base line, the distance on the range scale at which the lightning echo rises to saturation will be found to agree with the distance between the radar and the stroke. A drawing of a typical stroke return is shown in Fig. 9. Echo intensity can be

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16 Myron G. Ligda, "Lightning Detection by Radar," Bulletin American Meteorological Society, XXXI (October, 1950), pp. 279-283.

estimated by adjusting the gain control so that the noise is just perceptible. Returns which saturate the A-scope are strong; those which reach 2/3 saturation are moderate; those which reach 1/3 saturation are weak.

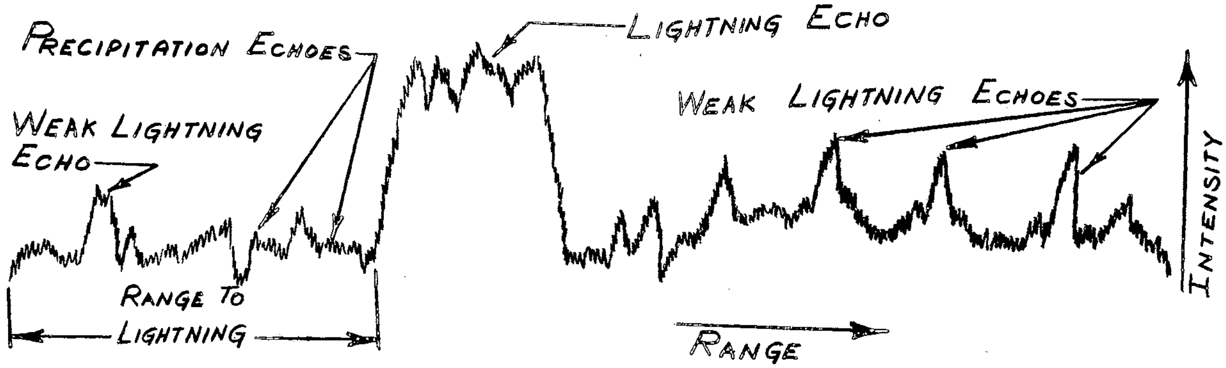

Fig. 9. Comparison of lightning and precipitation echoes on the expanded A-scope.

In equatorial regions the relative humidity is much greater than in the temperate areas. For conditions of approximately equal turbulence, storms in the tropics will be more heavily laden with water than those occurring in other portions of the world. Consequently the echoes from such storms may be expected to be somewhat in excess of those in different latitudes.[17] These climatic differences tend to place restrictions upon the radar requirements as outlined in the last chapter. In a case of this sort it may be more profitable to use S-band radar to avoid excessive atmospheric attenuation associated with high tropical water vapor content. Nevertheless, for purposes of study, the meteorological conditions that give rise to radar

17 U.S.A.F., A.F. Manual 105-30, <u>op. cit.</u>, p. 14.

echoes may be divided broadly into two classifications.[18] The first group is characterized by relatively small and well defined regions of localized precipitation. This generally results from precipitation in unstable air masses, and from frontal systems in which the air is conditionally or completely unstable. Cold-front thunderstorms and showers are examples of precipitation in conditionally unstable frontal systems. Tropical thunderstorms and showers are generally related to precipitation in unstable air masses. Cumulus congestus and certain other cloud types give rise to "active convective situations" wherein precipitation in the cloud does not reach the ground.[19]

The second category is typical of large and widespread areas of precipitation. This group includes precipitation in stable air masses, and in frontal systems in which the air taking part in the upglide movement is relatively stable. Widespread precipitation generally results from the mechanical lifting of stable air over mountains or from the upglide movement in warm fronts. Nimbostratus clouds are frequently associated with these synoptic conditions.

While these classifications are helpful, weather situations frequently arise which cannot be assigned exclusively to either of the foregoing groups. The experience of the weather observer is perhaps the most important factor in such circumstances.

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18 Kerr, op. cit., pp. 626-627.

19 Kerr, loc. cit.

Furthermore, typhoons, hurricanes and other severe storms of tropical origin encompass wide areas. These phenomena have individual characteristics and probably should be treated in a separate category. Also, it should be noted in passing that neither warm fronts nor cold fronts produce visible radar echoes.[20] Rather it is the precipitation associated with these fronts that give radar returns.

Maynard[21] has photographed several of the above weather echoes on the plan position indicator. Also, Mather[22] has pointed out that a certain amount of distortion may be introduced into the scope return due to poor resolution. A long pulse period elongates the return radially, giving the impression of a greater depth than actually exists. Poor horizontal resolution tends to widen the echo perpendicular to the radius on the plan position indicator, while poor vertical resolution tends to widen the echo perpendicular to the radius on the range height indicator. According to Mather, however, range attenuation tends to minimize the effects of low horizontal and vertical beam width resolution. The results of both Maynard's and Mather's studies are listed below.

1. Cold Front Precipitation. This generally appears as a band of well defined echoes on the plan position

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20 U.S.A.F., A.F. Manual 105-30, op. cit., p. 15.

21 R. H. Maynard, loc. cit.

22 John R. Mather, "Investigation of the Determinations of Precipitation Echoes of Radar," Bulletin American Meteorological Society, XXX (October, 1949), pp. 271-277.

indicator. The echoes may break up and join several times in their movement across the scope. The horizontal diameter of echoes from cold fronts is generally smaller than from warm fronts. This is because returns from cold fronts are commonly associated with convective cells of relatively small diameter as compared with the regions of precipitation usually present in warm fronts. The height of the cold front precipitation echo is predominantly greater than from a warm front due to the greater vertical development of the cells. The structure and relative activity of the cold front can frequently be estimated from the echo intensity, spacing, area of coverage, velocity of movement and vertical extent. Very light precipitation resulting from a weak cold front is often not detected by the radar.

2. Squall Lines. Precipitation resulting from squall lines show a band arrangement of echoes moving across the PPI-scope.

3. Thunderstorms. This is one of the most readily identifiable types of echoes. It appears as a bright, dense core with sharp boundaries. Ordinarily the center of the echo appears higher than the edges. A rough estimate of the vertical structure and development may be obtained by observing the return on the PPI for several angles of elevation, up to the point at which the echo fades.

4. Showers. On the plan position indicator showers are

usually located at random positions and have rather hazy, indistinct boundaries. Their speed and direction is generally determined by the winds aloft.

5. Warm Front Precipitation. Echoes arising from warm front precipitation usually cover a wide irregular area. The echo intensity varies continuously as a consequence of the characteristic change of rain from light to moderate intensity.

6. Occluded Front Precipitation. Warm occluded front precipitation echoes are similar to those from warm front precipitation. Cold occluded front precipitation echoes produce a return similar to cold front precipitation, but generally over a larger area.

7. Nimbostratus. The precipitation associated with these clouds is usually dispersed over a wide area. Nimbostratus clouds generally occur in blankets over distances much greater than the range of the radar. As a result the return on the PPI-scope frequently appears as a mass of brightness concentrated about the center and merging into blackness at the outer range circles. To the observer, the impression is that the radar is at the center of the disturbance. When the beam is directed upwards at an elevation angle of 90° with respect to the earth, the base and top of precipitation layers can be measured directly from the range reading on the scope.

8. Typhoons and Hurricanes. No other storm has been known to produce such a distinctive echo for any length of time as the tropical hurricane. Photographs taken by the United States Navy[23] and by the University of Florida[24] show the circular pattern appearing about the "eye" of the storm.

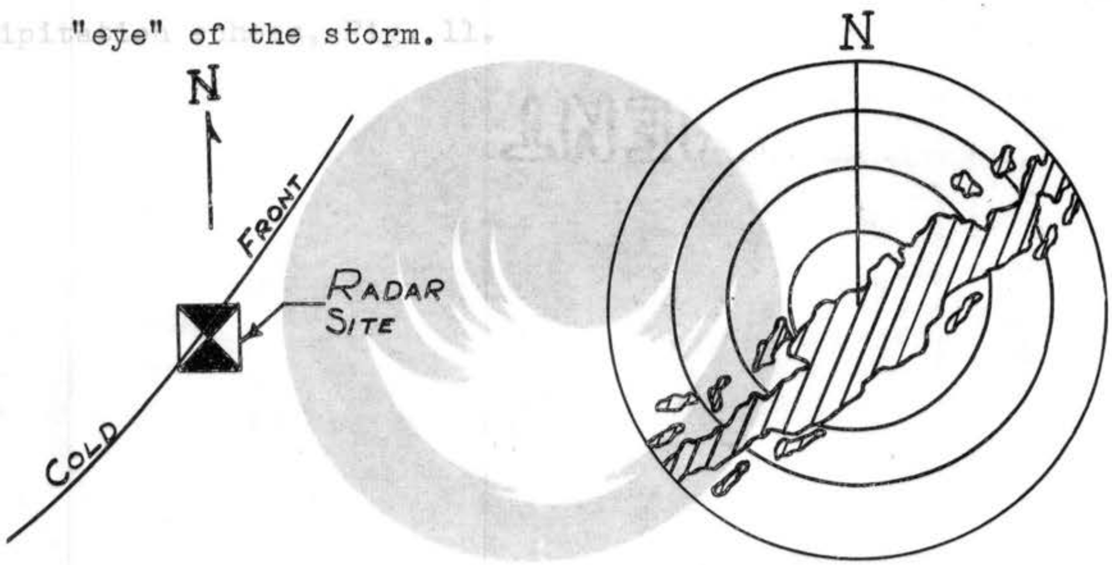

Fig. 10. Cold front and precipitation echoes from frontal thunderstorms as observed on the PPI-scope.

Fig. 10 is a redrawing of the photograph of precipitation echoes occurring along a line of thunderstorms in advance of a cold front.[25] The SCR-584 radar was situated at Spring Lake, New Jersey on July 16, 1944. The picture was taken at 1746 (5:46 P.M.) Eastern War Time. Each range circle represents 20,000 yards.

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23 Kerr, op. cit., p. 639.

24 M. H. Latour and D. C. Bunting, Radar Observations of a Florida Hurricane, August 26-27, Bulletin Series No. 29, III, Florida Engineering and Industrial Experiment Station, College of Engineering, University of Florida, (October, 1949).

25 U.S.A.F., A.F. Manual 105-30, op. cit., pp. 35-40.

On December 18, 1944 a plan position indicator recorded precipitation echoes from a typhoon occurring near the Philippine Islands.[26] The electrical characteristics of the radar were equivalent to the SCR-615-A. The "eye" of the storm and the rotary motion of the winds are discernible from the precipitation echoes, Fig. 11.

Fig. 11. A reproduction of a PPI-scope photograph of echoes associated with a typhoon near the Philippine Islands.

The United States Air Force has developed a very efficient method of transmitting radar weather data such as the above. The "Radar Precipitation Echo Report", or rarep code,[27] as it is commonly referred to, provides all the information for plotting a plan position indicator record at a distant weather station. If such a system were not available, television or facsimile would be required.

A number of measurements can be made with radar that are

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26 Ibid., p. 78.

27 Ibid., pp. 23-28.

frequently of great meteorological value. It has been noted previously that radar provides fairly accurate data on the velocity of cold front advance. Operating experience indicates that if the velocity of front movement is computed on the basis of distance traveled during 15 minute intervals, the results are well within the required accuracy.

In Fig. 12, a method is shown for determining the altitude of the base and top of a reflecting layer of nimbostratus.[28]

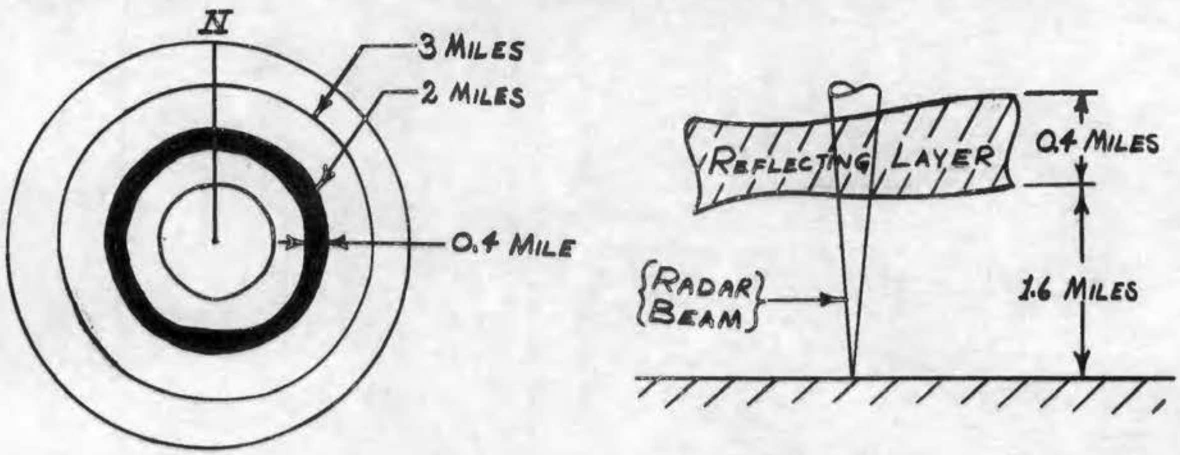

Fig. 12. The determination of the height of a reflecting layer. The beam is directed straight up. The line on the plan position indicator and the parabolic radiator rotate, but the direction of the beam does not change. The range circles are at one mile intervals. A heavy return is observed on the scope between 1.6 and 2.0 miles on the range scale. With this method the height of the top and bottom, and the thickness, of the stratification can be read directly from the range scale. This information was obtained using an X-band radar at Boston, Massachusetts, on May 21, 1943.

28 Ibid., p. 77.

It is frequently important to know the vertical extent of the echo source when it is not directly overhead. For example, Workman and Reynolds[29] have reported that electrical activity begins for most storms in the New Mexico area when the thunderhead reaches 31,000 feet. This activity was also observed to cease when the echo producing portion of the cloud subsided below 24,000 feet. Furthermore, they have established that the negative charge center is approximately 1.5 miles above the cloud base and near the region of maximum vertical convection. The positive charge center was located approximately one-half mile above the negative charge center and shifted from the vertical axis in the direction of the storm movement. These

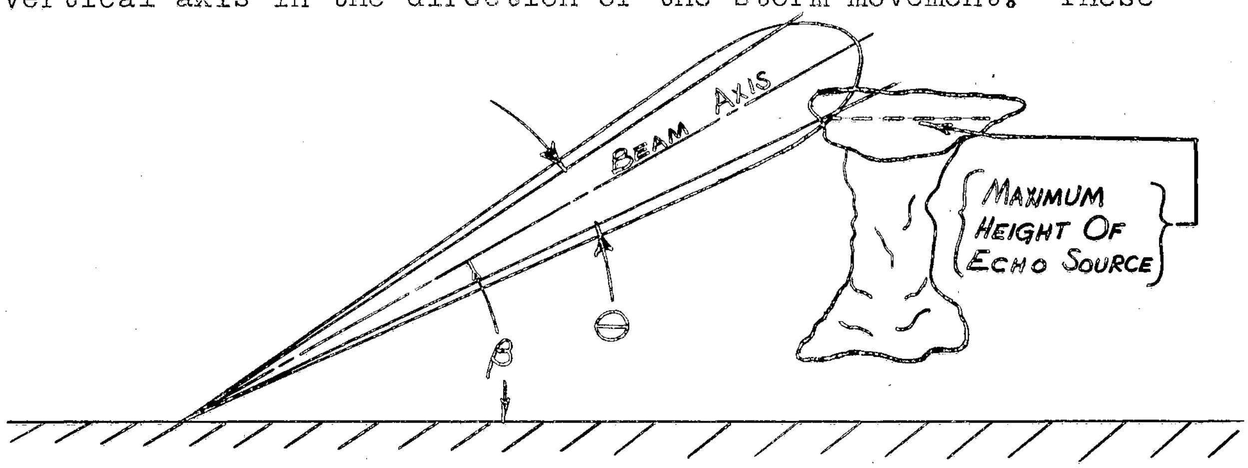

Fig. 13. The measurement of the vertical extent of echo sources.

dimensions may read directly from the range height indicator. However, for radars employing the plan position indicator, another technique must be resorted to for such measurements. In Fig. 13 it is seen that the echo would just fade from the screen

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29 E. J. Workman and S. E. Reynolds, Thunderstorm Electricity, Final Report, Research and Development Division, New Mexico School of Mines, Appendix A.

when the elevation is increased above the angle at which the lower edge of the radiation lobe just grazes the echo producing upper limit. The maximum height of the precipitation level is, consequently,

$$h = \left[r \operatorname{Sin}\left(\beta - \frac{\theta}{2}\right) \right], \text{ where} \qquad (5)$$

h is the height of echo producing level (in the same units as r),
r is the slant range as read directly from the PPI-scope,
β is the indicated elevation angle in degrees, and
θ is the beam width in degrees.
The method of estimating the extent of vertical development is, therefore, to increase the elevation of the antenna and observe the indicated angle and slant range at which the echo just fades. Equation (5) can then be applied.

Another phase of this study that has been under investigation is the use of radar for measuring turbulence in convective cells. The development of the range height indicator has given this study added impetus. Fig. 14 is adapted from Radar Storm Detection.[30] The vertical cross section through a thunderstorm is displayed on the range height indicator. The set employed was an X-band radar having a peak power of 70 kilowatts. To measure vertical extent accurately this equipment used a 1° vertical beam width. The storm is seen to reach to a height of 35,000 feet. The convective cell, reaching an altitude of 6 miles, is about 60 miles from the set. This picture emphasizes

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30 U.S.A.F., A.F. Manual 105-30, op. cit., p. 76.

the importance of height finding radar for studying the growth rate and development of such cells. A very clear impression of the convective column as a distinct part of the thunderstorm is conveyed by this precipitation echo.

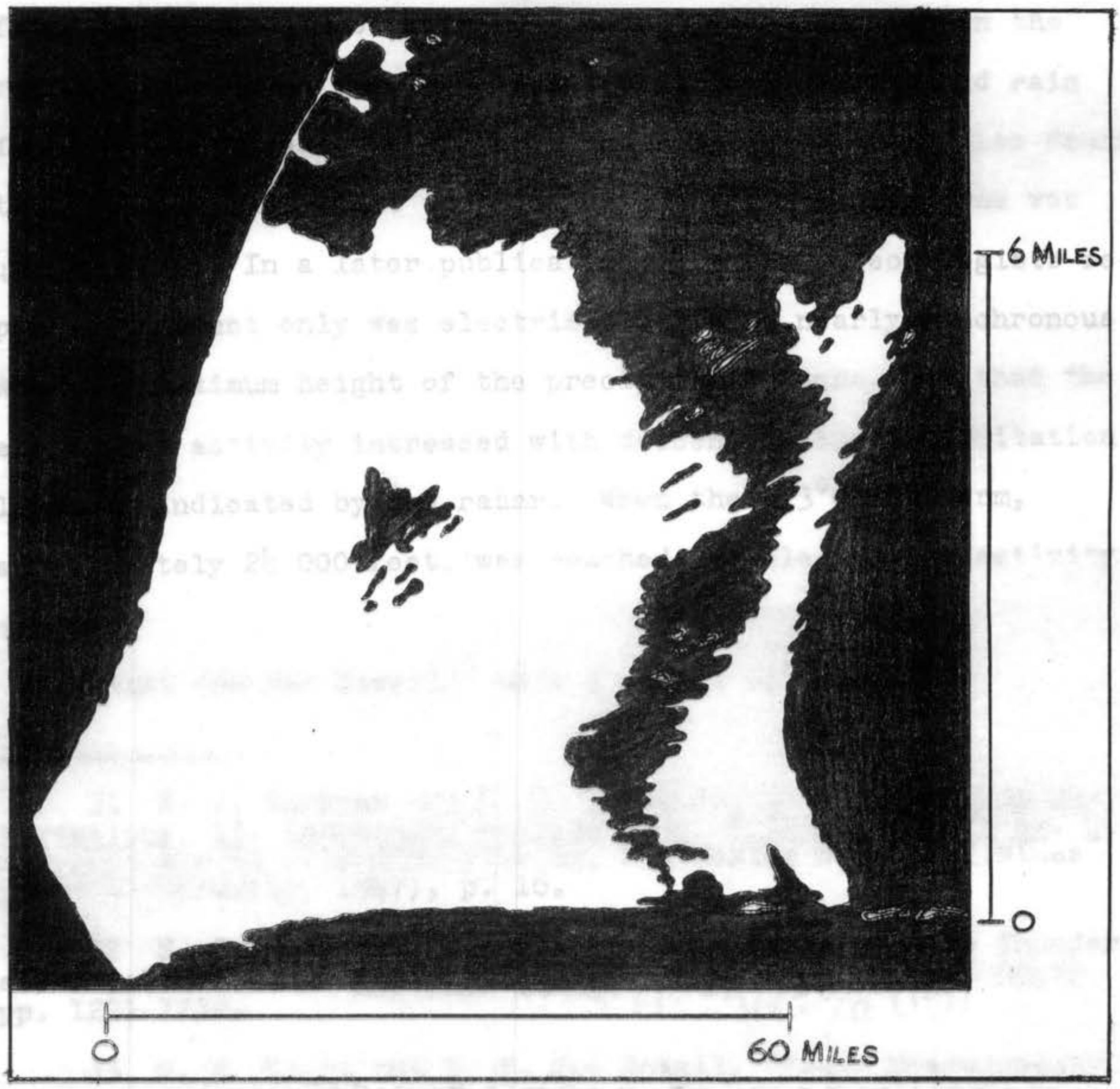

Fig. 14. The vertical cross section through a thunderstorm as observed on the range height indicator.

So much important work has been done on thunderstorm cell growth that the contributing research workers will be cited individually. Workman and Reynolds[31] observed the life cycles of the cell to be approximately 30 minutes in tests conducted in New Mexico. The initial appearance of precipitation echoes was found to be associated with the convective column within the rapidly developing cumulus cloud. Visible lightning and rain followed the appearance of these radar returns. They also found that the maximum height to which any convective cell grew was 49,000 feet. In a later publication,[32] these meteorologists reported that not only was electrical activity nearly synchronous with the maximum height of the precipitation echo, but that the electrical activity increased with descent of the precipitation level as indicated by the radar. When the -13°C isotherm, approximately 24,000 feet, was reached the electricity activity ceased.

Hilst and Mac Dowell[33] made a series of studies of

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31 E. J. Workman and S. E. Reynolds, I. Thunderstorm Observations, II. Laboratory Observations, Progress Report No. 4, Research and Development Division, New Mexico School of Mines (October-December, 1947), p. 16.

32 E. J. Workman, "Electrical Activity Related to Thunderstorm Cell Growth," Physical Review, 74 (July-December, 1948), pp. 1231-1232.

33 G. R. Hilst and G. P. Mac Dowell, "Radar Measurements of the Initial Growth of Thunderstorm Precipitation Cells," Bulletin American Meteorological Society, XXXI (March, 1950), pp. 95-99.

thunderstorms using SCR-615-B and AN/TPS-10 radar. They found that rapid vertical development is accompanied by extremely high cell drafts. This phenomena is manifested as an up draft in the growing stage and a down draft in the dissipating stage. The RHI-scope was used for all observations in connection with the vertical growth and development of the cell. It is the opinion of the writer of this thesis that this is a most significant discovery. As has been pointed out in connection with the physical characteristics of tornadoes, the tornado is characterized by extremely large vertical and horizontal wind velocities. It seems reasonable to conclude, therefore, that high growth rates are an exclusive feature of tornadic cells. Furthermore, a means of differentiating between the incipient and fully developed tornado may be the difference in the growth rates of the two. The determination of the "critical growth rate" of tornadoes, if one exists, must of necessity be the subject of extensive research based upon statistical studies.

Mather[34] has found that the convective cell increases horizontally and vertically at the same time. Perhaps this also may be a means of distinguishing tornadoes. It seems reasonable that a tornadic cell would be characterized by excessive horizontal as well as vertical development. Mather also observed that cells become larger both vertically and horizontally with increasing potential instability of the air mass. Likewise, increased potential stability is evidenced by small vertical and

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34 Mather, op. cit., pp. 276-277.

horizontal development. This may be valuable in predicting where the tornadic convective cell may be expected to form, since instability is one of the "empirical criteria" as explained in Chapter II. Thus the work of Mather, together with that of Workman and Reynolds would infer that tornado observers should look for large rapidly growing cells. The rapid growth requirement is a particularly necessary aspect of the investigation. Miller[35] has made the significant discovery that while rapidly growing cells are regions of strong turbulence, large cells that are not developing rapidly are areas of heavy precipitation with little or no turbulence. Moreover turbulent conditions are more severe just before entering and after leaving the main radar echo. Turbulence will also be influenced to a certain extent by the altitude at which it exists.

Bemis[36] has observed that convective cells exhibit a marked sloping effect. Cells have been noted to be tilted as much as 70° from the vertical. Mather[37] attributes this to wind shear at high altitudes. In addition, Bemis verified the higher reflectivity of water as compared to snow and ice. The radar

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35 Robert W. Miller, 1st. Lt. A.C., Res., "The Use of Airborne Navigational and Bombing Radars for Weather in Radar Operations and Verifications," Bulletin American Meteorological Society, XXVIII (January, 1947), pp. 19-28.

36 Alan C. Bemis, "Weather Radar Research at M.I.T.," Bulletin American Meteorological Society, XXVIII (March, 1947), pp. 115-117.

37 Mather, loc. cit.

return from the portion of the thundercloud below the zero isotherm, or freezing level, was much greater than above it.

Byers and Coons[38] noted that echoes that have rapid vertical development and which widen, particularly at the top, are indicative of severe thunderstorms. RHI photographs of scope returns exhibiting a "drippy" appearance were found to be associated with precipitation occurring within the cloud, but not reaching the ground.

Harrison and Beckwith[39] conducted a series of investigations into the presence of hail in the Denver area. They found that airborne radar is not only effective for detecting the presence of thunderstorms, but also is useful for delineating the size, shape, and intensity of the storm. Moreover, it appears that certain types of radar are capable of showing the rate of change of large water drop concentrations in and near the storm cloud. The radar is thus able to provide a contour pattern of the rainfall rate. Meteorological studies indicate that such a contour is extremely valuable in determining regions of heavy turbulence. These workers have also found that radar is useful for indicating the presence of hail. When light rain changed abruptly to heavy rain, the precipitation echo intensity increased. Hail formed at the same time. This appears to be

38 Horace R. Byers and Richard D. Coons, "The 'Bright Band' in Radar Cloud Echoes and Its Probable Explanation," Journal of Meteorology, IV (1947), pp. 75-81.

39 H.T. Harrison and W.T. Beckwith, "Studies on the Distribution and Forecasting of Hail in Western United States," Bulletin American Meteorological Society, XXXII (April, 1951), pp. 119-131.

very helpful in predicting hail, but unfortunately the radars now in service are not capable of distinguishing large raindrops from hail by observation of the precipitation echo.

These results suggest an additional check that may be used in predicting tornadoes. As discussed in the first chapter, hail is frequently present in tornadic cells. If the observer were to set the brilliance on the PPI-scope and the RHI-scope to just above the threshold value, a strong increase in echo intensity would indicate this condition. The use of an A-scope would be particularly well suited to observing such an abrupt increase in echo intensity.

A number of unusual phenomena have been observed on the scope, and while at present they do not appear to be very significant, future research may indicate the value of such peculiarities. One of the first observed was the presence of a series of "banded structures". These "bright bands" are associated with precipitation echoes. They constitute a series of light and dark bands across the scope return. This phenomena has been observed on the PPI and RHI-scopes. A number of theories have been advanced to explain them, but some difference of opinion exists. The Air Force[40] explains their presence on the PPI-scope, when using SCR-584, as due to the rotation of the radiation lobe. Byers and Coons[41] give three prominent

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40 U.S.A.F., A.F. Manual 105-30, op. cit., p. 35.

41 Byers and Coons, op. cit., p. 75.

meteorological characteristics of bright bands:

1. They always appear straddling the freezing level.
2. They are associated with stratified clouds.
3. They appear in relatively weak and broken clouds from which little or no rain can be observed.

These observers conclude that when such bands appear very few drops fall out of the colloidially unstable air, or that the drops grow smaller through evaporation if precipitation does occur. Cunningham[42] is not entirely in agreement with this theory, but he is in accord with the stratified cloud concept.

Austin and Bemis[43] explain these bands by means of still another theory. It is their view that three phenomena produce banded structures. These are the effect of coalescence, the effect of melting, and the effect of the fall velocity of the precipitation particles, the latter being the most important. They also show that these bands verify the existence of snow above and rain below the freezing level. The thickness of the band is believed to bear a rough relationship to stability. Such bands also give an approximate indication of the freezing level. Kerr[44] has observed this phenomena on the plan position

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42 Robert M. Cunningham, "A Different Explanation of the 'Bright Line'," Journal of Meteorology, IV (October, 1947), p. 163.

43 Pauline M. Austin and Alan C. Bemis, "A Quantitative Study of the 'Bright Band' in Radar Precipitation Echoes," Journal of Meteorology, VII (April, 1950), pp. 145-151.

44 Kerr, op. cit., pp. 638-639.

indicator in connection with precipitation echoes arriving shortly before a hurricane. He explains their presence as related to a large circulatory system which rotates about the center of the storm.

Another rather peculiar phenomena is the appearance of a "shadow" on the plan position indicator. This has been observed on the SCR-584, and is believed to be due to the reaction of the receiver to a very strong transmitted signal,[45] but not as the result of blocking by the storm. High noise level in the receiver and strong precipitation echoes occurring in this region are visible on the scope.

Whenever the power and sensitivity of a radar are great enough to detect targets at ranges in excess of those on the indicator, "second sweep echoes" appear. This means simply, that the elapsed time of a wave going from the radar to the target and back is in excess of the time allotted from the first sweep of the indicator, and must appear on the second sweep. This has been observed on the SCR-584 by Air Force personnel.[46] The maximum range of the indicator is 80,000 yards. However, the equipment will detect targets greatly in excess of this distance. In Fig. 15 it is seen that a target between 120,000 and 140,000 yards appears to be between 40,000 and 60,000 yards on the second sweep. The time necessary for the spot to move

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45 U.S.A.F., A.F. Manual 105-30, op. cit., pp. 21, 51.

46 Ibid., p. 32.

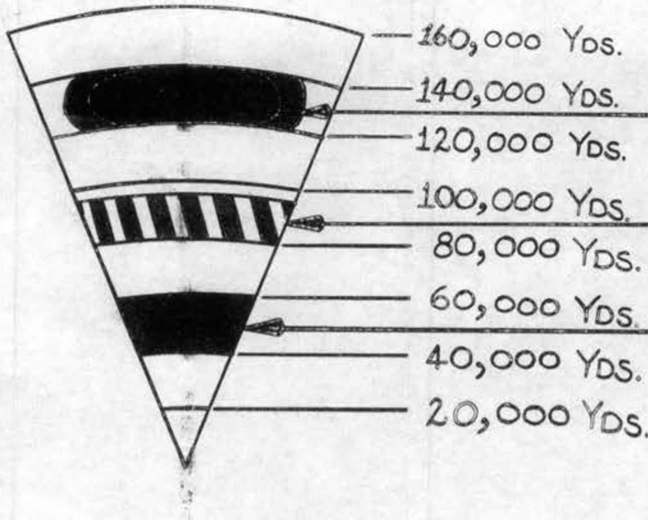

Fig. 15. Second sweep echoes.

from the end position back to the start of the sweep, flyback time, is equivalent to 16,000 range yards. This amounts to 32,000 yards overall, since one range yard is a yard out and a yard back. During flyback no targets are displayed on the scope. Therefore, if the target is at 80,000 yards or less, it appears at its proper range. If it is between 80,000 and 96,000 yards, it will not be detected. If it is in excess of 96,000 yards, it will have an apparent range of

Apparent Range in Yards = Actual Range in Yards - 80,000 Yards.

For other radars, different flyback times and different maximum ranges must be considered. It should be observed that second sweep echoes are distorted, or squeezed perpendicular to, but not along the radius. This is frequently helpful in recognizing these returns.

The information just presented is an up to date and reasonably comprehensive account of the significant advancements achieved with radar. The chapter would not be complete, however, without a comment concerning the reliability of the radar as a storm warning device. For instance, Workman and Reynolds[47] have reported that on certain occasions a radar return was observed to be very similar to those observed in severe thunderstorms, and yet no electrical activity was present. Harrison and Beckwith[48] have reported that in 10% of the cases studied radar was not effective in indicating the presence of hail. Miller[49] also found that under some circumstances radar could not be relied upon for identifying storm clouds. Furthermore, he states that while maximum turbulence is typically encountered in young, growing cloud structures just to the rear and just in advance of the main rain areas, this device is unsuited to a quantitative analysis of the exact degree of turbulence. It is known that he based his conclusions on the AN/APQ-13, which at the time he prepared his report was perhaps the best radar available for meteorological work. It is believed that the height finding radar and its accompanying range height indicator may prove to be the one means of determining the precise amount of turbulence. The Air Force[50] has reviewed the records of a Canadian weather-radar project conducted in the Summer of 1944 near Ottawa. An S-band radar was used in the investigation.

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47 Workman and Reynolds, Progress Report, op. cit., pp. 21-22.

48 Harrison and Beckwith, loc. cit.

49 Miller, loc. cit.

50 U.S.A.F., A.F. Manual 105-30, op. cit., pp. 14-15.

In 48 cases rain was definitely verified when a precipitation echo was received. The precipitation echo was always reported within a few minutes of the arrival of rain. In only 45 of 113 observations was electrical activity reported when the precipitation echo was observed at ranges less than approximately 60 miles. However, for ranges greatly exceeding 60 miles, thunderstorms were correlated with precipitation echoes in 11 out of 12 cases. In a similar series of studies conducted by the Air Force, using S-band radar in Panama, it was found that in 70 instances when precipitation echoes were received, 50 were definitely associated with rain. In 13 cases rain was expected, since thunder was heard. In 7 cases neither rain nor thunder was reported. No figures were given for the radar ranges of these storms.

The conclusion may then be drawn that radar, by itself, does not provide an absolutely certain method of storm recognition. Nevertheless, the equipment has been valuable in a sufficiently large number of storm situations to lead to the conclusion that its potentialities should not be overlooked. As was stated in the first chapter, a reliable tornado warning system should be an integration of all existing techniques. This means that radar should be checked against sferics and the empirical method whenever possible. This will be discussed in detail in the following chapter. It is this writer's firm belief that if tornadoes can be predicted, a coordinated method is the only available solution.

CHAPTER V

AN INTEGRATED METHOD OF TORNADO ANALYSIS

The main purpose of all of the previous discussion in this study has been to provide a comprehensive background, both electrically and meteorologically, of the possibilities and of the obstacles in the path of tornado identification. It must be kept in mind that in order to see a problem through to its solution, the research staff must constantly be mindful of: (1) what the problem is, (2) the means available for studying and attacking the problem, and (3) the necessary amount of ingenuity and originality for using the means available to the best possible advantage. This investigation has discussed the problem and the means now at the scientist's disposal for making future strides. While proposals for future study will be introduced in subsequent paragraphs, the writer does not presume that these suggestions necessarily possess the requisite amount of ingenuity as expressed in item (3). Nevertheless, these ideas have been considered carefully and they appear to be fruitful.

The importance of cooperation between the meteorologist and the engineer is once more emphasized. It seems reasonable that the first step in developing an effective warning system is to determine the seasons during which tornadoes are most likely to occur. This has been accomplished by Fawbush and Miller. For Oklahoma and surrounding states the spring, early summer and early autumn should be studied closely for tornadic activity. Naturally, all seasons of the year should be watched, but special attention should be paid to these critical periods. Also, the meteorological data should be compared with the empirical criteria. Simultaneously, microbarometric analyses should be made in the suspected areas determined from the empirical method. These two systems will serve to check each other. This phase of the warning must be conducted by reliable and experienced meteorologists. This work will serve to locate the anticipated danger areas.

The meteorologist should then alert the engineer concerned with the electrical phase of the warning system. The sferic detection system and its associated direction finder should be checked against the United States Army Signal Corps AN/GRD-1A, static direction finder. This will serve as a method of locating the sources of high energy sferics. The general direction from which the radiation emanates should be compared with the anticipated region of tornadic activity obtained by meteorological data. The radar should then be employed to explore these areas for characteristic signs. If precipitation echoes indicate rapidly growing cells, and if the sferic detector records high frequencies from this area, a warning should be posted. The main advantages of the radar will be to confirm all other methods and to pin point the location of funnel development.

The following recommendations are made concerning future research in the electrical phase of this problem:

1. The sferic detection system should be modified to include a filter to permit only the high frequency components to be displayed on the indicator. A suggestion

has been made that the filter should also activate a trigger circuit in such a manner that it could be connected into the AN/GRD-1A so that the equipment would only indicate high frequency sferic directions. The possibility of using frequency selective networks as a potential means of differentiating incipient from full grown tornadoes should be investigated. Wave form and period of lightning stroke radiation should be investigated with a view of assigning either or both of these characteristics to incipient and fully developed tornadoes. It is also possible that continued visual observations of the color of lightning may provide an additional qualitative check on other data.

2. The AN/APQ-13 radar has just arrived at the Oklahoma Experiment Station, Oklahoma Institute of Technology. It may be quite some time before statistical studies of precipitation echoes can be made. Nevertheless, the following recommendations should be considered. The most important characteristic of precipitation echoes from tornadic cells seems to be the high convective cell vertical growth rate. The AN/APQ-13 is equipped only for the plan position indicator and not for the range height indicator. The range height indicator is considered by the author to be an <u>absolute necessity</u> in order that significant progress can be made with radar. The use of AN/TPS-10A is urgently recommended. Even then it may be necessary to place some type of optical

magnifying system over the scope to measure growth rate accurately. Data should be collected with a view of establishing from statistical studies growth rates for incipient and tornadic conditions. The growth can be determined approximately when using AN/APQ-13 radar by taking readings of the height of the convective cell at intervals of 3 to 5 minutes.

The use of an A-scope and expanded A-scope is strongly advised. It is possible that lightning stroke radar returns, or precipitation echo intensities will have a characteristic behavior when originating from tornadic cells. Furthermore, since hail is associated with tornadoes, the method of Harrison and Beckwith for determining hail by radar should be investigated. The PPI-scope should be set for the threshold value of vision and should be observed for an abrupt increase in intensity. The A-scope or expanded A-scope should be set so that the precipitation echo is just visible. The indicator could then be watched for an abrupt increase in echo return, probably approaching saturation, when hail is formed.

The plan position indicator could be studied to determine the horizontal cross section of the cell at various altitudes. The cell diameter at various elevations, and particularly at the top, should be studied in an effort to acquire data on the relationship of such structures to tornadoes. The life span of the cell should be studied for tornadic and non-tornadic conditions. The vertical and horizontal structure of the cell should be observed and analyzed from inception through maturity to dissipation.

If the Experiment Station is successful in acquiring an AN/TPS-10A radar, extensive studies on the altitude, shape, and width of a vertical cross section of the cell should be undertaken as a possible means of checking potential instability of the air mass, and of predicting tornado formation. Also, the precipitation echoes displayed on the RHI-scope could be studied to determine contour patterns of rainfall rates. Since such information is known to be of value in determining areas of high turbulence, it may be useful in tornado research. Fawbush and Miller believe that wind shear is excessive in regions of high tornadic activity. Therefore, excessive sloping of the convective cell on the RHI may aid in tornado identification.

Future work will naturally suggest many other possibilities, but the proposals made here represent at least a beginning of a new line of study. It is hoped that these suggestions will be helpful.

CHAPTER VI

PRELIMINARY OBSERVATIONS

At the September 11, 1951 meeting of the Oklahoma City Section of the American Institute of Electrical Engineers, the author was privileged to interview Lt. Col. E. J. Fawbush and Major R. C. Miller of the United States Air Force. These officers are assigned to the Air Weather Service at Tinker Air Force Base, Oklahoma.

Fawbush and Miller have observed precipitation echoes from severe thunderstorms on AN/APQ-13 installed at their station. On one occasion Major Miller observed an anticipated tornadic cell on the radar scope. The precipitation echo appeared as a bright circle about the size of a five-cent coin at a range of about 60 miles. The sharpness of the edges and brightness of the center were observed to be of the same type as those of well developed thunderstorms occurring in connection with a cold front. Because similarities such as these do unfortunately exist, it cannot be stated that all bright and clear precipitation echoes are received only from tornadic cells.

Major Miller expressed the opinion that an extremely high convective cell velocity is the key to the difference between incipient tornadoes and fully developed ones. However, neither of these investigators have made a study of the horizontal or vertical growth rate of precipitation echoes.

Major Miller believes that the height of the convective cell is not necessarily related to the severity of thunderstorms or tornadoes over the Great Plains. He points out that in one instance a tornado was observed to have a cell height of only 22,000 feet, some 2,000 feet below the level of minimum electrical activity as reported by Workman and Reynolds in New Mexico.

Major Miller provided the author with a photograph of a tornado that struck Corn, Oklahoma on July 8, 1951 at 6:15 p.m. In Fig. 16 the funnel is clearly visible in its descent from the base of the thundercloud. Near the bottom of the funnel a fuzzy appearance may be noted due to mud and debris being drawn upward. This tornado developed when the six meteorological requirements, as set forth in the empirical method, were fulfilled.

On the afternoon of Thursday, October 4, 1951, at approximately 5:00 p.m., the author observed the first precipitation echoes on AN/APQ-13 at Stillwater, Oklahoma. Radar returns were noted from clouds containing considerable moisture as they passed overhead. Professor William Hardy, head of the department of meteorology, explained that precipitation was actually taking place, but that the water was evaporating before reaching the ground. The base of a number of these clouds was observed to have a vertical structure with uneven bottoms, giving an appearance of rain falling from such bodies. The most intense echoes, however, were observed to be almost due south from 55 to 60 miles from the radar.

By 7:00 p.m. of the same day lightning and thunder could be seen and heard. At 8:00 p.m. one storm was observed to be 35 miles south southeast of Stillwater. As it moved northward it

Fig. 16 Photograph of a tornado which struck Corn, Oklahoma, July 8, 1951.

veered east and passed ten miles east of the station. From its path as seen on the radar, it was estimated to have struck slightly north of Tulsa, Oklahoma. The author heard the midnight weather report for October 4, 1951, on radio station KVOO, Tulsa. Rain and electrical activity were reported between 10:00 p.m. and 11:30 p.m. For the first time bright bands were observed on the radar scope as the storm passed.

At 9:00 p.m. of the same evening a second storm was tracked on the radar from 45 miles south southwest until it passed directly overhead. The storm began as four individual convective cells that could be seen to grow rapidly as they approached the station. In fact, both Dr. Jones and the author could readily see the evidence of such growth about every four or five minutes. This would seem to indicate that growth rate study would be of definite value in identifying tornadic cells. By the time the storm had reached the station, a continuous bright line of precipitation echoes could be noted. The depth of the echoes was so great that the storm produced an approximately elliptical scope return. One reason for the greater depth was due, of course, to the fact that as the lighter rain areas approached Stillwater they produced an echo, while at longer ranges they were not detectable. However, the rapidity with which these echoes increased did not justify this as the sole explanation. It is the author's opinion that the storm was still developing as it passed overhead. The amount of lightning and thunder observed certainly bears this point out.

When the storm was directly overhead, the radar was switched to the 4 mile range and the antenna was elevated to 35°. The scope illuminated almost completely. It was possible to pick out the centers of electrical activity by observing the most intense regions of the echo.

On the morning of Friday, October 5, 1951, at 9:45 a.m., the author observed precipitation echoes at 65 miles due north and 35 miles north northwest. These results were checked against the hourly weather report received in the teletype room in the meteorology department. A cold front was moving across northern Oklahoma and lightning and thunder activity were reported in the Ponca City area. Between 12:45 a.m. and 3:00 p.m. of the same day, the author and numerous witnesses from the Oklahoma Institute of Technology observed a line of precipitation echoes as they approached the station from the northwest. At 12:45 a.m. the front was approximately 8 miles northwest of the station. At 1:45 p.m. it was approximately 3 miles northwest of the station. As it approached it dissipated very rapidly. By 2:10 p.m. precipitation echoes had shrunk from a line 50 miles wide to only 10 miles wide. As it passed directly overhead, only very light rain occurred. By the time it had moved 5 miles south of the station, only two or three widely scattered echoes could be noted. These results seem to further encourage growth and decay rate studies in predicting thunderstorm severity.

On Sunday, October 14, 1951, at 3:10 p.m., the precipitation echoes from a thunderstorm associated with a cold front were photographed. In Fig. 17 the precipitation echoes are

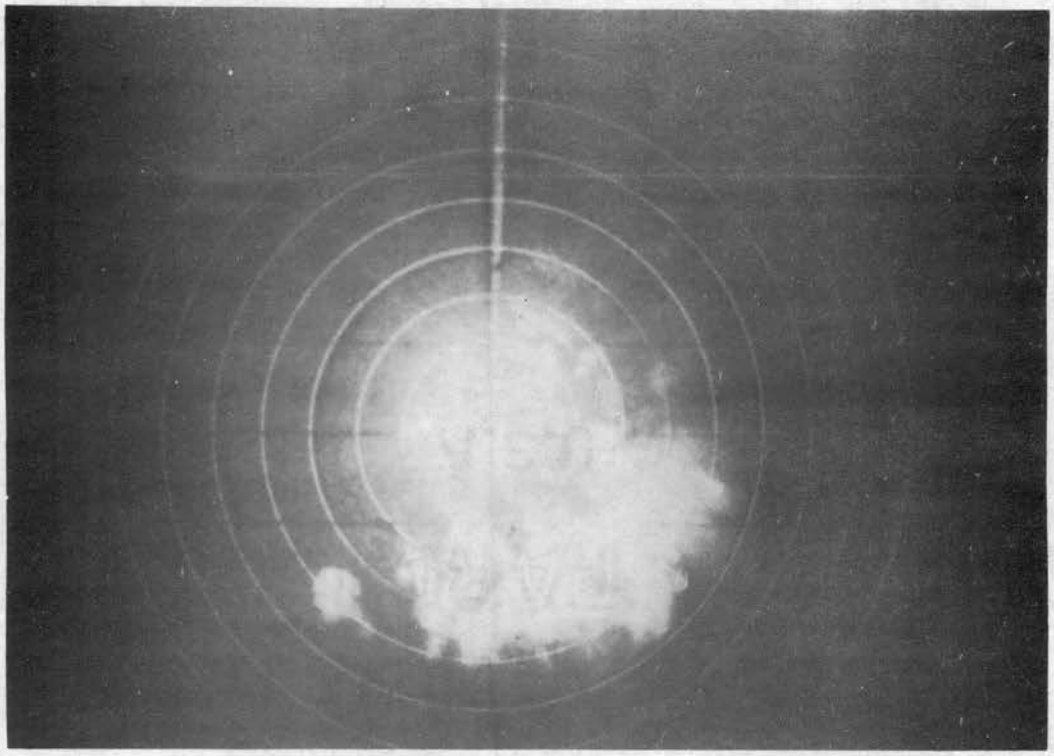

Fig. 17. Precipitation echoes from a cold front thunderstorm of October 14, 1951, as observed on the 50 mile range.

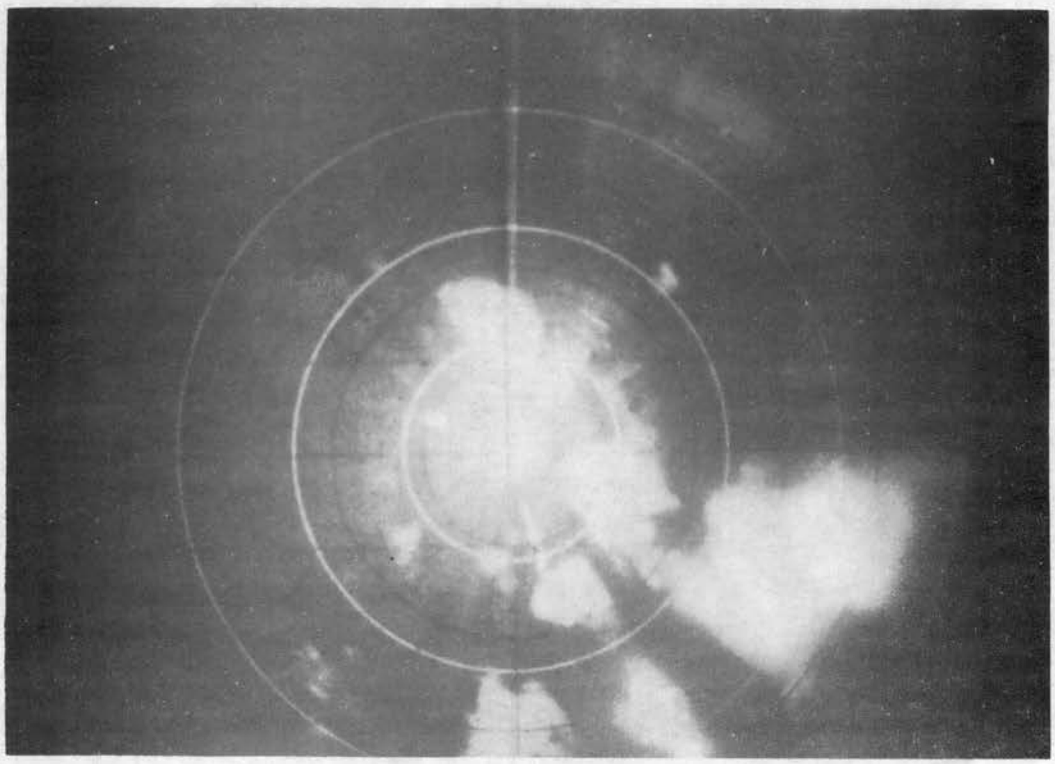

Fig. 18. Precipitation echoes from a cold front thunderstorm of October 14, 1951, as observed on the 20 mile range.

shown photographed from the radar scope. The range was set to 50 miles, and therefore, each circle represents a 5 mile radial increment. The antenna elevation was 4° and the brightly illuminated line extending straight upward from the center is the approximate direction of geographical north. The brilliance control was set to high intensity and the film was exposed for 8 seconds. The aperture setting of the camera was 4.5 (maximum open) and Kodak Panatomic-X film was used. The bright band phenomena is clearly visible in the lower right hand portion of the photograph.

When this picture was taken, the portion of maximum electrical activity of the thunderhead had already passed over the city. A study of the photograph shows the region of maximum brightness to be approximately 20 miles southeast of Stillwater. The curvature of the leading edge of the echoes can be seen to have the approximate shape and direction of motion of a frontal system moving from northwest to southeast. In Fig. 18 the same thunderstorm is photographed on the 20 mile range. Each range circle represents 5 miles and the antenna elevation is 1°. The exposure time, brilliance setting, lens setting, film, and time of photographing are the same as for Fig. 17. Switching to the twenty mile range has the effect of providing a close-up of the storm area. The author noted that the thunder and lightning were somewhat more intense shortly before the pictures were taken. In fact, the rain from overhead was very light at the time of photographing, but it was extremely heavy about 15 minutes before.

On Tuesday, October 17, 1951 a very weak cold front passed over Stillwater. During the entire day clouds could be observed whose base formed a series of parallel vertical lines. Precipitation was falling from them, but it evaporated before reaching the ground because the air below was so dry. Further evidence of precipitation was substantiated by the fact that the author observed a rainbow west of the city at 8:00 a.m. Between 10:00 a.m. and 4:00 p.m. the author observed precipitation echoes from these clouds which showed the same type of parallel lines emanating from their bases. No lightning or thunder was reported and Stillwater received no rain during the day. At 8:17 p.m. the photograph shown in Fig. 19 was taken. The range of the radar was set at 20 miles and therefore each circle represents 5 miles. The antenna elevation was set at 15°. Shortly before the picture was taken very light rain was reported, but there was definitely no lightning or thunder present. Information received from the department of meteorology indicated that a very weak cold front passed over Stillwater between 5:00 p.m. and 6:00 p.m. of this day. The weak and hazy echoes support the relatively small amount of precipitation observed. Echoes such as these frequently occur also in connection with widely dispersed precipitation associated with warm fronts. When this picture is compared to the photographs in Figs. 17 and 18, it is readily seen that severe thunderstorms produce much stronger returns than clouds which have only a very low water content.

The author observed that these echoes built up and faded very rapidly. In an interview with Professor Hardy it was

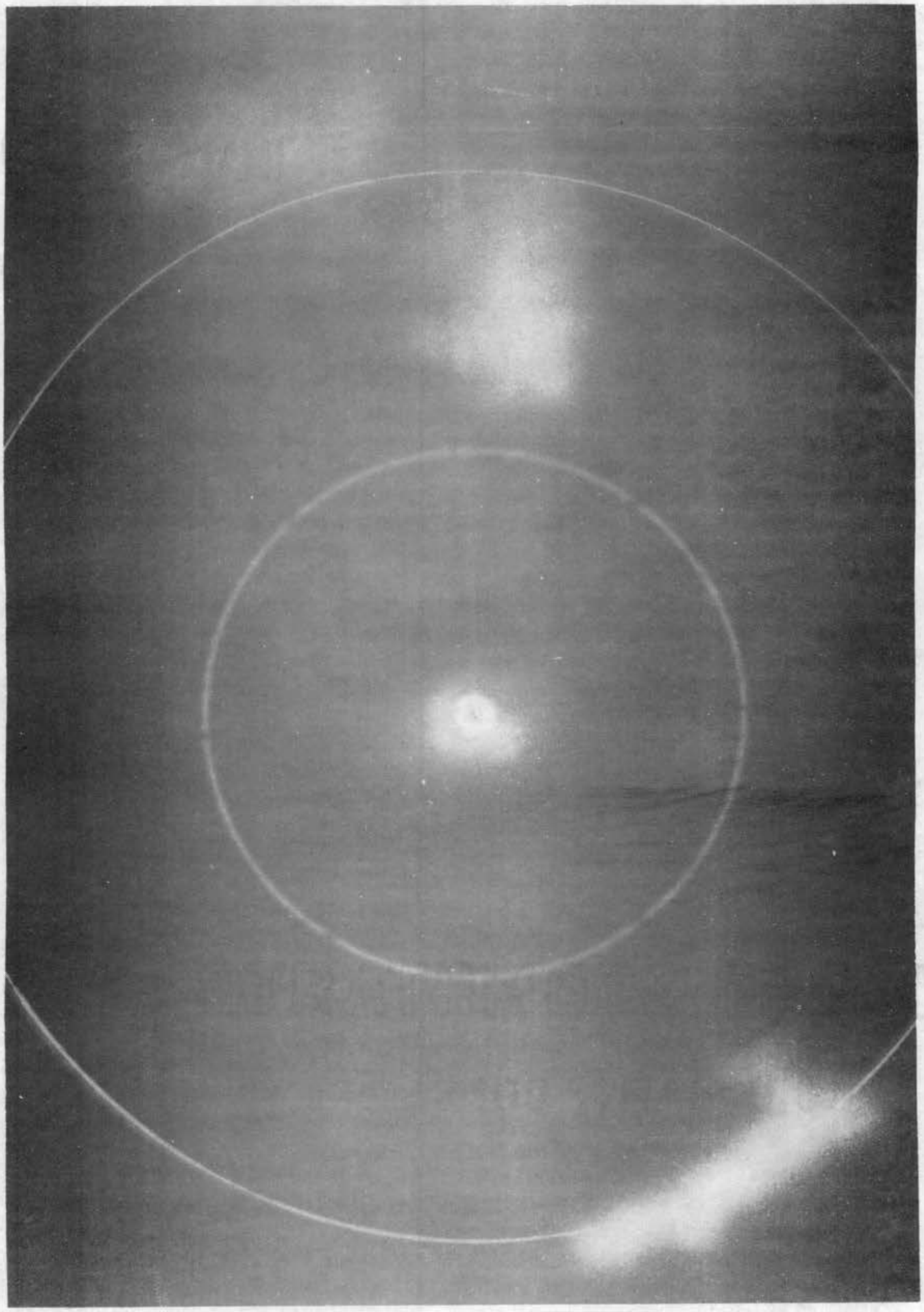

Fig. 19. Precipitation echoes from a weak cold front of October 17, 1951.

learned that such build up and dissipation may occur frequently in the Great Plains region of the United States. Professor Hardy later commented that he watched the hail storm which struck Stillwater in June of 1950 build up. This storm later developed into three tornadoes southeast of Stillwater.

On Sunday, October 21, 1951 a cold front passed over the radar station between 10:30 p.m. and 11:00 p.m. Lightning was visible to the north from about 7:00 p.m. until midnight. No thunder was heard and no rain fell in the vicinity of Stillwater. In Fig. 20 a photograph of precipitation echoes is shown. The radar was set on the 50 mile range and each circle represents 5 miles. This photograph was taken at 9:10 p.m. The antenna was elevated 5°. Professor Hardy provided the author with the hourly weather report. Rain was reported at Ponca City, Oklahoma at 9:00 p.m. The precipitation echo from the Ponca City rain can be observed to be 35 miles almost due north. The author measured the height of the convective cell of this storm by increasing the antenna elevation until the echo just faded. The indicated elevation angle was observed to be 10.5° for the target at 35 miles. Attention is called to the fact that all ranges and range circles are calibrated in terms of nautical miles. Since one nautical mile is equivalent to 6080.27 feet, the altitude of the convective cell is

$h = r \sin(\beta - \frac{\theta}{2}) = (35 \times 6080.27) \sin (10.5^\circ - 1.5^\circ)$, or

$h = 33,250$ feet.

It should be noted that the vertical beam width was reduced from 90° to only 3° by removing the barrel stave reflector.

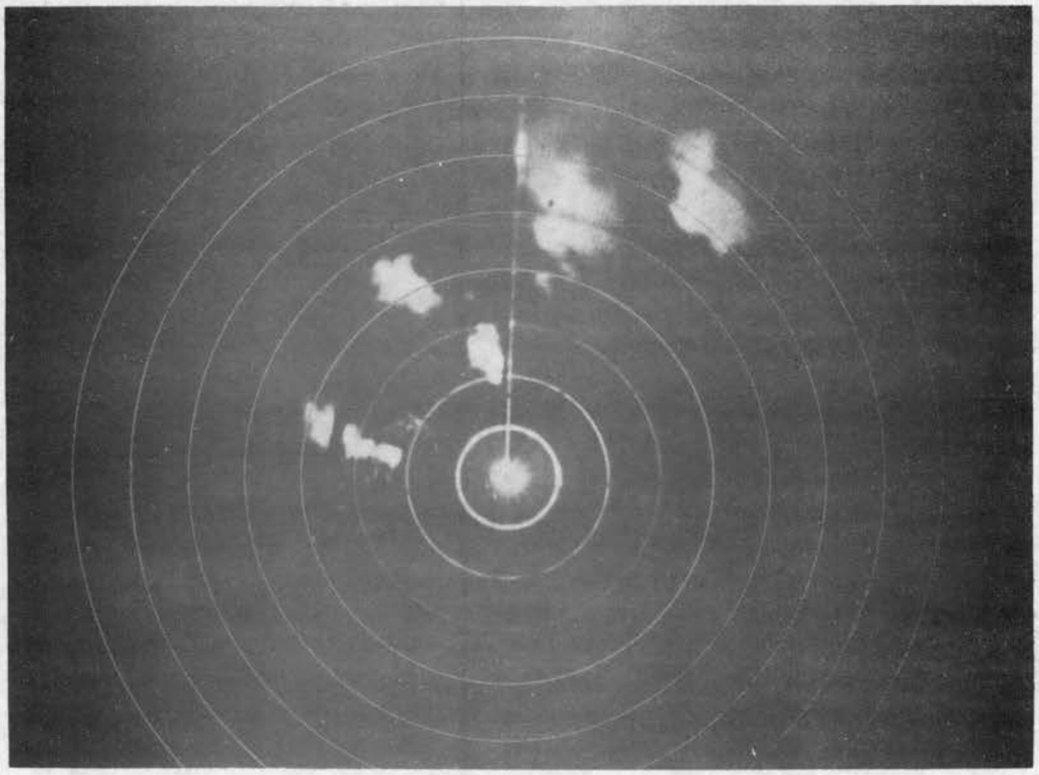

Fig. 20. Precipitation echoes from a thunderstorm over Ponca City, Oklahoma, October 21, 1951 at 9:10 p.m.

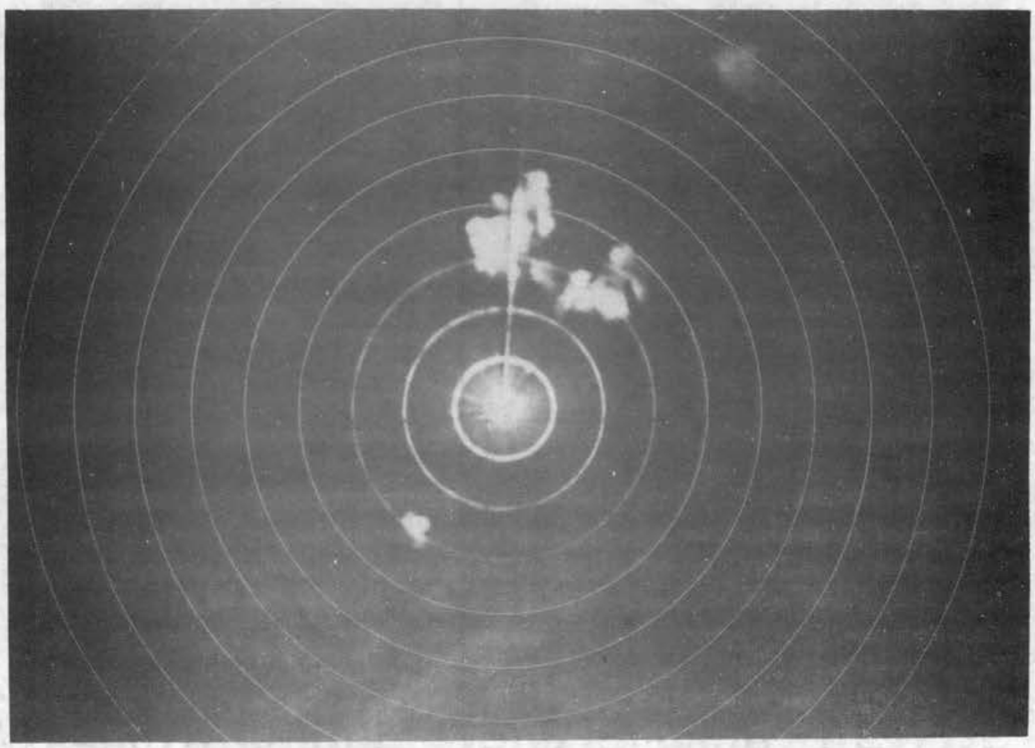

Fig. 21. Precipitation echoes from a thunderstorm over Ponca City, Oklahoma, October 21, 1951 at 9:35 p.m.

The second photograph of this storm was taken at 9:35 p.m. and is shown in Fig. 21. The radar had the same settings as for Fig. 20. A comparison of these photographs shows an eastward movement of the echoes. This is in agreement with actual conditions, as Stillwater received no rain. A study of these pictures clearly shows the presence of bright bands.

The weather report as heard on radio station KVOO, Tulsa, for the evening of Sunday, October 21, 1951, indicated that the thunderstorms over the state were caused by a rapidly moving cold front. A tornado was reported at Gage, Oklahoma, at 6:15 p.m. of this day. No damage was done however, as the funnel did not reach the ground. Straight line winds were reported by the Oklahoma City weather station to be approximately 55 to 60 miles per hour. Lightning and thunder were also reported from Oklahoma City.

In Fig. 22 a photograph is shown of the Oklahoma City storm as it approached from almost due south. The radar was set on the 50 mile range and each circle represents 5 miles. The antenna elevation was set at 4° and the picture was taken at 11:40 p.m. As the storm approached the station, an area immediately in front of the main precipitation echo began to produce a radar return. This return was not as intense as the main echo and had the "porous" appearance shown in the figure. It is the author's belief that rain in advance of the main storm area was being driven by the strong winds. As it came within sufficient range, the radar was able to detect the rain. It was also observed that the entire advancing rain area produced this return

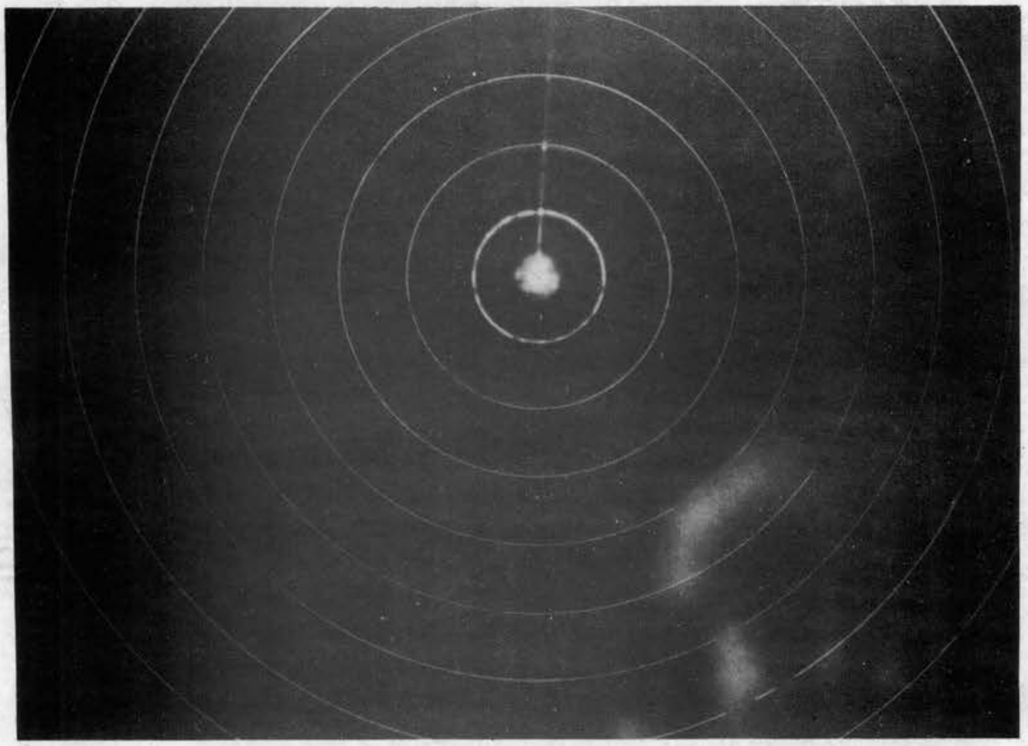

Fig. 22. Precipitation echoes from a thunderstorm of October 21, 1951, approaching Stillwater, Oklahoma from the south.

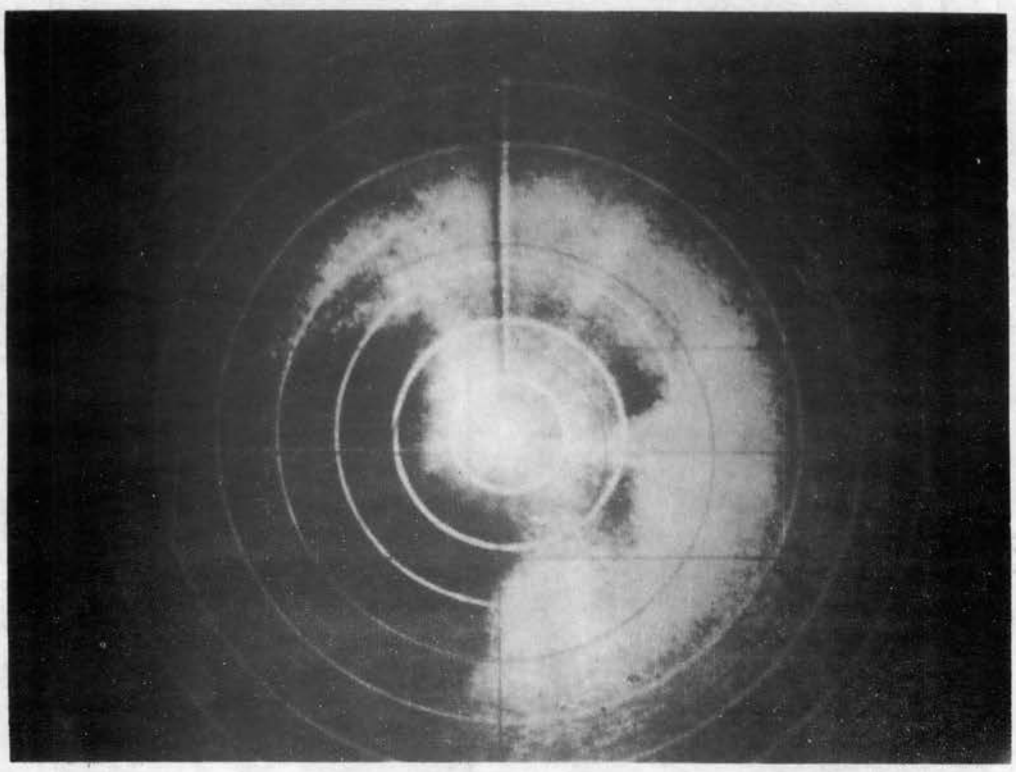

Fig. 23. Precipitation echoes from a rainstorm of October 26, 1951 over Stillwater, Oklahoma, at 9:15 p.m.

simultaneously. Therefore, it is not believed that this was due to the storm growing. Circumstances such as these dictate the necessity for carefully observing precipitation echoes as soon as they come within the range of the radar.

Shortly before the photograph was taken the winds aloft were determined by the radar. It was noted that a period of 15 minutes was required for the center of the main precipitation echo to move from the 40 mile range circle to the 35 mile range circle. Accordingly, 5 nautical miles were covered in 15 minutes. Therefore, the upper wind velocity was

$$\text{Velocity} = \left[\frac{5 \text{ nautical miles}}{\left(\frac{15}{60}\right) \text{ hours}}\right] = 20 \text{ nautical miles per hour.}$$

In terms of statue miles this would become

$$\text{Velocity} = \left[\left(\frac{6080.27}{5280}\right) \times 20\right] \text{ statue miles per hour} = 23 \text{ mph.}$$

By observing the path which the precipitation echo followed, the direction of the wind was determined to be moving from the south southwest. As the author closed the radar station, he observed intense lightning from the south.

On Friday, October 26, 1951 a cold front passed over Stillwater. Heavy precipitation began at approximately 9:00 p.m. Lightning was observed south of the city, but no thunder could be heard. In Fig. 23 the precipitation echo appears as a semi-circular arc extending from the 15 to the 25 mile range circle. This photograph shows that precipitation echoes from rainstorms produce the porous return previously referred to. By contrast thunderstorms produce solid bright returns with sharp edges.

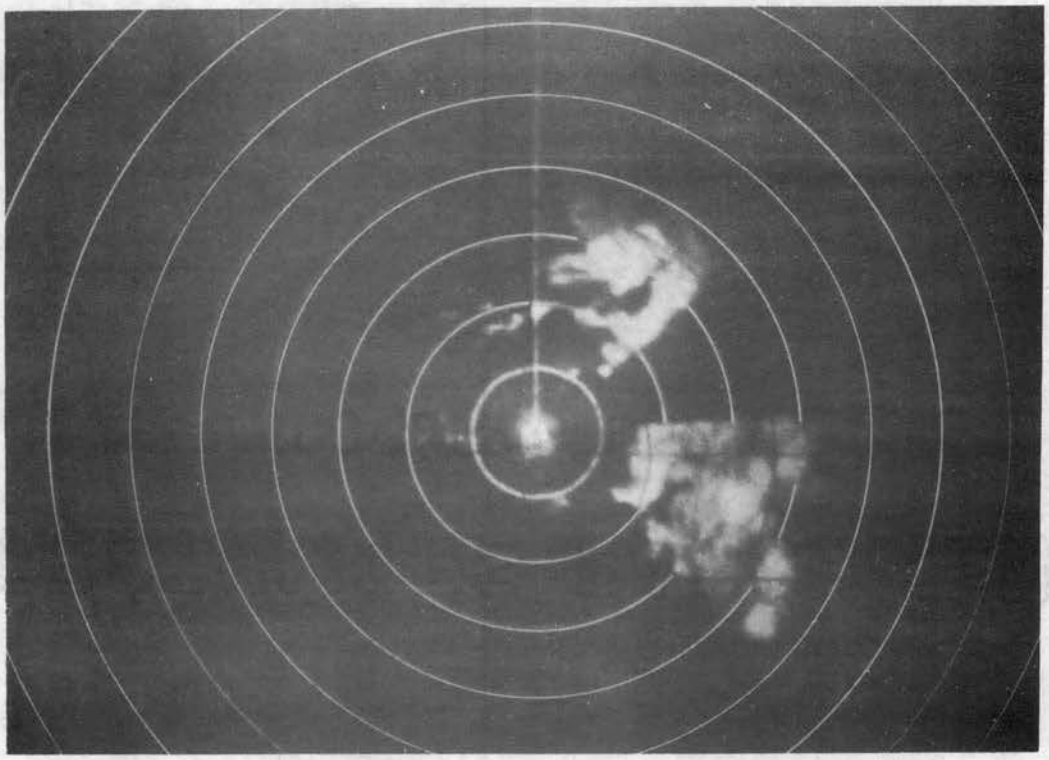

Fig. 24. Precipitation echoes from a rainstorm of October 26, 1951 over Stillwater, Oklahoma, at 9:40 p.m.

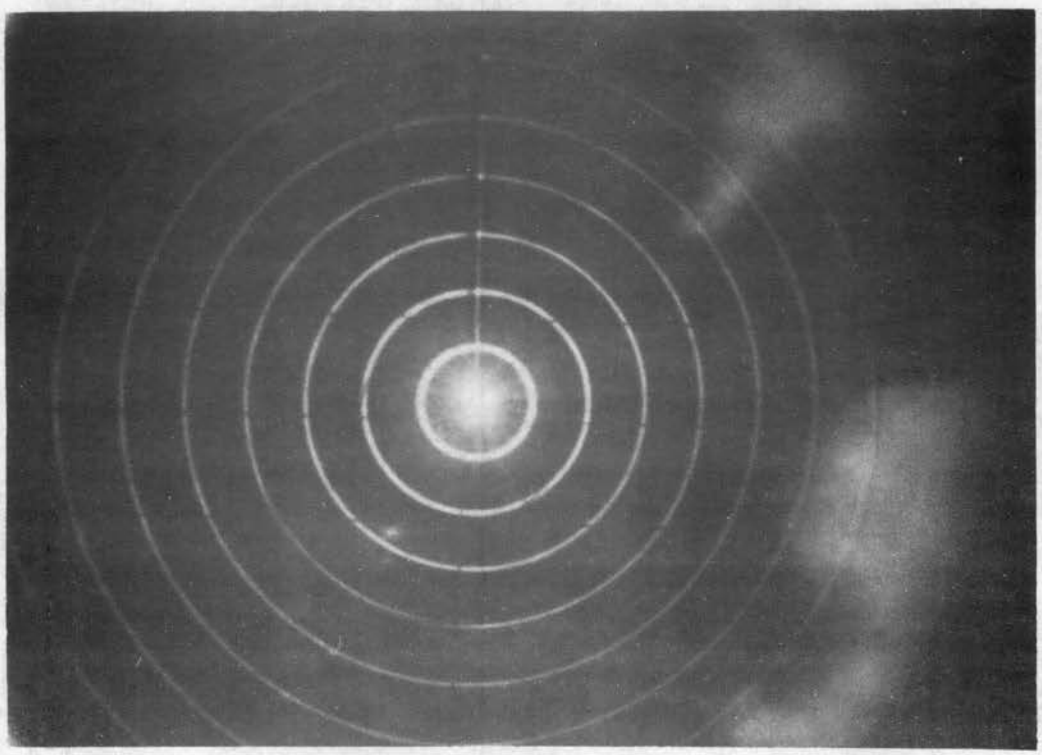

Fig. 25. Precipitation echoes from a rainstorm of October 26, 1951 over Stillwater, Oklahoma, at 11:30 p.m.

When the photograph was taken, the radar was set to the 10 mile range. Each range circle represents a one mile radial increment. This picture was taken at 9:15 p.m., with the antenna elevation at 10 degrees.

In Fig. 24 the precipitation echoes from the same storm are shown as they appeared on the scope for a setting of 4 miles. Each range circle represents a one mile radial increment, and the antenna was elevated to 3°. The porous return from the rain area is evident and a blank portion may be noted to the east, which is believed to be due to the football stadium. The photograph was taken at 9:40 p.m.

In Fig. 25 precipitation echoes from the same source are shown photographed on the 50 mile range. Each range circle represents a radial increment of 5 miles and the antenna was elevated to 5°. A study of the picture shows the movement of the precipitation to the southeast. The photograph was taken at 11:30 p.m. when the rain from overhead was very light.

The results of the foregoing observations lead to the conclusion that radar is a most effective indicator of the rapidly varying meteorological conditions which exist in the Great Plains. Whenever moisture is present in sufficient quantity to produce a radar return, the growth or decay of its associated cloud can be studied. Furthermore, its path can be followed and the winds keeping it in motion can be calculated. If the requisite synoptic conditions permit the formation of a convective cell within the cloud, the height of the column can be measured. The radar may be envisioned as an X-ray machine that records, in a qualitative manner, the extent and delineation of water within a cloud.

On numerous occasions clouds have been observed which gave the appearance of a high water content. However when these same clouds were investigated with radar, they produced no return. The rapidly changing meteorological conditions have also been noted. In one instance a precipitation echo about the size of a quarter coin was noted 10 miles northeast of the station with the radar set to the twenty mile range. Before the camera could be set up and adjusted to take the photograph, a period of approximately seven minutes, the echo had shrunk to about half its original size and moved almost to the extremity of the 20 mile range.

It is therefore believed that this study has provided definite evidence that growth and decay rates are the major factors to investigate in a comprehensive study of severe thunderstorms and tornadoes. If this work could be continued with the RHI type of radar as well as the present model, it appears that significant progress might be made in tornado tracking.

APPENDIX A

In Chapter III the formula for the gain, G, of a microwave radiating system was given. This relationship is derived in the following discussion. The concentration of energy in a particular direction results from the characteristics of the dipole and the paraboloid. The gain of the dipole in the direction of maximum radiation is

$$G_d = \frac{3}{2} .$$

The gain of the paraboloid is

$$G_p = \left[\frac{8\pi A}{3\lambda^2}\right] .$$

The overall gain is the product of these two, or

$$G = \left(G_p G_d\right) = \left[\frac{3}{2}\left(\frac{8\pi A}{3\lambda^2}\right)\right] = \left[\frac{4\pi A}{\lambda^2}\right] .$$

Some authors[1] take A to be the apertural area rather than the effective area, as was done in this thesis. In accordance with the mathematical symbols of Chapter III this gives

$$A = B$$

or, the effective area is equal to the apertural area. In Chapter III, A was taken to be $\frac{2}{3}$ B. If A is taken to be equal to B, equation (1) becomes

$$P_r = \left[\frac{TPB^2}{4\pi r^4 \lambda^2}\right]$$

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1 Hugh Odishaw, et. al., Industrial Electronics Reference Book, p. 653.

which agrees with equation (34.17) in the Westinghouse Industrial Electronics Reference Book.[2] Accordingly, this change would increase equations (2), (3), and (4) by a factor of $\left(\frac{3}{2}\right)$ or 1.5. Furthermore, Odishaw[3] takes the beam width to be

$$\Theta = \left[\frac{\lambda}{D}\right]$$

instead of 85% of λ/D as was done in Chapter III. Therefore equations (2), (3), and (4) would be multiplied by a factor of

$$F = \left[\frac{1.5}{0.85}\right] = 1.765$$

to be in general agreement with Odishaw's results. The disagreement arises from the fact that the empirical results are subject to different degrees of approximation by the individual investigators.

It was also pointed out in Chapter III that the range of the radar will be influenced by the bandwidth and the noise level of the receiver. Equation (1) will now be modified to include the effects of thermal noise. The theoretical lower limit of received power, set by thermal noise is[4]

$$P_t = kT_k(\Delta f) \quad \text{watts, where}$$

P_t is the thermal noise power in watts,
$\underline{k}$ is the Boltzmann's constant (1.37×10^{-23} watt-seconds/degree Kelvin), T_k is the absolute temperature in degrees Kelvin, and Δf is the receiver band width in cycles per second.

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2 Ibid., pp. 653-654.

3 Ibid., p. 647.

4 Odishaw, loc. cit.

From practical experience it has been found that the threshold signal must be from 5 to 100 times greater than the theoretical noise power to appear as a distinct radar echo. Under these conditions,

$$P_{min} = (mP_t) \text{ watts, where}$$

P_{min} is the minimum detectable signal strength in watts, and m is a factor between 5 and 100.

If equation (1) is solved for the range, and P_{min} is used instead of P_r,

$$r = \sqrt[4]{\frac{TPB^2}{9\pi mkT_k \lambda^2(\Delta f)}} . \qquad (6)$$

A similar expression may be derived for equations (2), (3) and (4). It would appear from equation (6) that the range could be increased indefinitely by decreasing the band width. It must be remembered, however, that the target definition is adversely affected by a narrow band. In addition, a value of Δf corresponding to a maximum signal to noise ratio has been determined approximately as

$$\Delta f = \left[\frac{1.2}{\tau}\right] ,$$

where τ is the pulse duration.

Although it was not mentioned previously, the power versus time relationship is very important in specifying certain specific radar properties. In Fig. A below one complete cycle from the beginning of one pulse to the start of the following one is shown. The quiescent time is Q and the period between

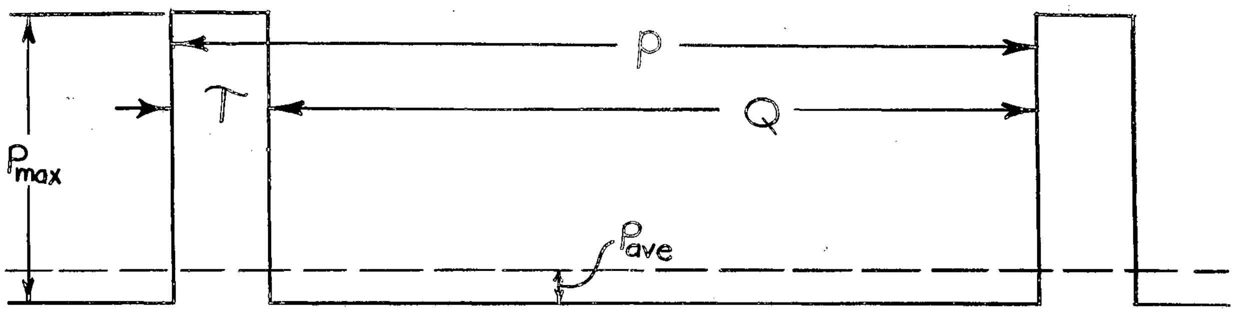

Fig. A. Maximum and average power versus time.

successive cycles is designated by p. It follows that

$$p = (Q + \tau).$$

Since the pulse recurrence frequency is $1/p$, it follows that the ratio of the pulse width to the pulse recurrence period can be defined as the duty cycle, U, where

$$U = \left[\frac{\tau}{p}\right].$$

The average power is equal to the maximum power integrated over the pulse width and divided by the pulse recurrence interval,

$$P_{ave} = \frac{1}{p}\int_0^{\tau} P_{max}\, dt = \left[\frac{P_m \tau}{p}\right] = (UP_{max}).$$

This may also be expressed as

$$P_{ave} = \nu \tau P_{max} \tag{7}$$

where ν is the pulse recurrence frequency. If a particular radar has a typical 1 microsecond pulse width and a pulse recurrence interval of 1000 microseconds, the pulse recurrence frequency is 1000 pulses per second and the duty cycle is 0.001. A magnetron capable of 100 kilowatts peak power would produce heating in proportion to an average power of

$$P_{ave} = (UP_{max}) = (0.001 \times 10^5) = 100 \text{ watts}.$$

The maximum power, P_{max}, is the same as the transmitted power, P, as given in Chapter III. If optimum signal to noise frequency band criteria is substituted into equation (7),

$$P = P_{max} = \left[\frac{P_{ave}}{\tau \mathcal{V}}\right] = \left[\frac{P_{ave}}{\left(\frac{1.2}{\Delta f}\right)\mathcal{V}}\right] = \left[\frac{(\Delta f)\ P_{ave}}{1.2\ \mathcal{V}}\right] .$$

If this expression is substituted into equation (6), an expression for the range in terms of the average power may be obtained. The result is

$$r = \sqrt[4]{\frac{TP_{ave}B^2}{10.8\pi mkT_k \mathcal{V}\ \lambda^2}} . \tag{8}$$

This relationship implies that the range is proportional to the fourth root of the average power. As stated previously the range is really determined by the energy per pulse. This may now be demonstrated by substituting equation (7) into (8),

$$r = \sqrt[4]{\frac{TB^2P\ \tau}{10.8\pi mkT_k\ \lambda^2}} . \tag{9}$$

If the substitution,

$$H = \sqrt[4]{\frac{TB^2}{10.8\pi mkT_k\ \lambda^2}}$$

is introduced, then equation (9) becomes

$$r = H\sqrt[4]{P\tau} = H\sqrt[4]{\text{Energy Per Pulse}} . \tag{10}$$

This conclusion is in agreement with the result obtained in Chapter III and Fig. 6. This provides a mathematical check on the conclusion that a radar capable of detection at very short ranges and possessing high range resolution must have an extremely high peak transmitted power if a long range is to be achieved.

APPENDIX B

LIST OF MATHEMATICAL SYMBOLS

<u>Symbol</u>	<u>Quantity Represented</u>
a	mean radius in meters of all the cloud droplets illuminated by the radar
a_i	the drop radius in meters of the <u>i</u>th drop illuminated by the radar
A	the effective area in square meters of the radar radiating system
B	the apertural area in square meters of the radar radiating system
c	the velocity of light in free space in meters per second ($3 \cdot 10^8$ meters per second)
d	the pulse length in space in meters
D	the diameter of the paraboloid in meters
e	the dielectric constant of the radar target
E	the electric field intensity in volts per meter acting on the cloud droplet dipole
Δf	the radar receiver band width in cycles per second
F	a multiplying factor
G	the overall gain of the radar radiating system
G_d	the gain of the dipole antenna
G_p	the gain of the paraboloid
h	altitude in feet or meters
H	a constant
k	Boltzmann's constant (1.37×10^{-23} watt-seconds/degree Kelvin)
K	an atmospheric attenuation constant
m	a multiplying factor between 5 and 100

Symbol	Quantity Represented
n	the total number of drops illuminated by the radar beam
N	the drops per unit volume illuminated by the radar beam
p	the time in seconds from the beginning of one pulse to the beginning of the following one
P	the peak or maximum transmitted power in watts
P_i	the power density incident upon the target in watts per square meter
P_r	the power received in watts
P_{ave}	the average power transmitted in watts
P_{max}	the maximum or peak power transmitted in watts
P_{min}	the minimum power detectable in watts
Q	the quiescent period in seconds between pulses
r	the slant range to the target in meters or miles
R	the line of sight distance to the horizon in miles
S	a factor representing the amount of scattering of radio energy
t	time in seconds
T	the effective target area in square meters
T_k	the absolute temperature in degrees Kelvin
U	the radar duty cycle
V	the volume of the target effectively illuminated in cubic meters
V_m	the maximum volume of the target effectively illuminated in cubic meters
W	the energy in Joules
β	the indicated elevation angle in degrees

Symbol	Quantity Represented
θ	the radar beam width in degrees or radians
λ	the wavelength in meters
ν	the pulse recurrence frequency in cycles per second
π	3.14159 the ratio of the circumference of a circle to its diameter
ρ	the dipole moment of the cloud droplets
σ	the radar cross section in square meters
Σ	a summation sign
$\int$	an integral sign
τ	the pulse width in seconds

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THESIS TITLE: Radar Analysis of Tornadoes

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